

PERMANENT MAGNET ALTERNATOR  
CONTROL BY MEANS OF  
MAGNETIC SATURATION

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AND  
FRANK C. ANDERSON

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SATURATION

by

William L. Aitkenhead, Lieutenant, U. S. Coast Guard  
B. S., U. S. Coast Guard Academy, 1946

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Submitted in Partial Fulfillment  
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1953



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Submitted to the Department of Naval Architecture and Marine Engineering on 25 May, 1953 in partial fulfillment of the requirements for the degree of Naval Engineer.

## ABSTRACT

The permanent magnet alternator as a source of power has been impractical until comparatively recent times. The advent of powerful new magnetic materials similar to the "Alnico" types has made such machines more practical, and has caused renewed interest in their development and use.

One serious limitation of a permanent magnet alternator is the lack of control over the output voltage. If voltage control by means of a simple electrical means could be developed, the usefulness of the machine would be vastly increased. The purpose of the present investigation is twofold: (1) to analyze the magnetic circuit in a permanent magnet alternator when the stator becomes saturated from an independent source of magnetomotive force, and (2) to devise a means of voltage control for this type of machine.

If the stator of an alternator is visualized as a toroid and a continuous winding of many turns is wound thereon, it is possible to induce within the toroid, a continuous unidirectional flux by means of a direct current in the winding. When a permanent magnet rotor is inserted in the stator, it also tends to send flux lines through the iron of the stator. However, in portions of the stator the flux from these two separate sources tend to flow in the same direction and in portions they tend to oppose. Analysis of the magnetic circuit under these conditions shows that the air gap flux is reduced because of the overall increase in the reluctance of the flux paths facing the permanent magnet. At constant speed, the voltage is proportional to the flux in the air gap and hence if the air gap flux can be controlled the output voltage can be controlled by toroidal saturation. Furthermore the analysis and experimental verification show that the percent of voltage control by means of magnetic saturation may be increased by building into the machine additional leakage paths for the flux, although the magnitude of the voltage output is thereby reduced. The saturation of the stator appears to have no serious effects upon the waveform of a properly designed machine, or on machine heating.





The power expended to achieve voltage control by this method is nominal within limits, although by no means compares with the control afforded by the wound-rotor type installation. The machine tested was found to maintain constant voltage for a variable load of from 190 to 21 watts (or variation of 89%) with an expenditure of direct current power in the control winding of 23.7 watts, or 11.9% of the initial ac output power. Furthermore, the power expended for control in this device is greatest when the load power is least, making an automatic voltage regulation system using a feedback loop practical.

Two practical methods of designing more efficient control systems based on the principle of toroidal saturation are (1) develop permanent magnet materials with a higher incremental permeability (the slope of the "recovery line"), and (2) design the alternator with the maximum leakage possible consistent with the magnitude of the voltage output required.

The theoretical analysis of the magnetic circuitry is supported by the experimental results to within the accuracy of the various assumptions.

Thesis Supervisor: Professor D. C. White  
Title: Assistant Professor of Electrical  
Engineering

The power expended in driving voltage control by this method is minimal within limits, although by no means negligible when the control is effected by the wound-rotor type induction. The power factor was found to maintain constant voltage for a variable load of from 100 to 11 watts (or variation of 8%) with an expenditure of almost constant power in the control winding of 15.5 watts, or 11.2% of the initial no output power. Furthermore, the power expended for control in this device is greatest when the load power is least, making an automatic voltage regulation system using a feedback loop practical.

Two practical methods of designing more efficient control systems based on the principle of constant induction are (1) device between magnet inductance with a slight inductance in parallel; the slope of the "no-load line" and (2) design the amplifier and the voltage output possible constants with the weights of the voltage output regulated.

The theoretical analysis of the magnetic circuit is supported by the experimental results in which the accuracy of the various measurements.

These experiments were conducted by Professor H. B. White, Assistant Professor of Electrical Engineering, Massachusetts Institute of Technology.



Cambridge, Massachusetts  
May 25, 1953

Professor E. B. Millard  
Secretary of the Faculty  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of  
Naval Engineer, we submit herewith a thesis entitled  
"Permanent Magnet Alternator Control by means of  
Magnetic Saturation".



### ACKNOWLEDGMENTS

The authors wish to express their appreciation to Professor David C. White for his advice and encouragement; and to Professor Charles Kingsley, Jr. for his helpful suggestions on magnetic circuitry.

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The author wishes to express their appreciation to  
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## I. INTRODUCTION

A permanent magnet alternator is a synchronous generator which has a permanent magnet for its source of magnetomotive force instead of the wound rotor electromagnet used in the conventional alternators. As recently as 1940, permanent magnet generators were impractical because suitable magnetic materials were not available. With the advent of magnets which can better withstand the effects of temperature, demagnetizing fields, and vibration, the permanent magnet alternator is now being used in applications where a compact source of small amounts of power is required.

Permanent magnet alternators have an inherent disadvantage compared to machines excited by direct-current. Because the flux from the permanent magnet is an intrinsic quantity, there is no direct way to maintain a constant terminal voltage under varying conditions of loading and speed.

Although the characteristics of the permanent magnet cannot be altered, it is possible to regulate the output voltage of a permanent magnet alternator by establishing control over the circuit traversed by the lines of magnetic flux from the permanent magnet.

The magnetic circuit between each pair of poles of a permanent magnet rotor consists of two air gaps and a path in the iron of the stator, all in series. Control of this magnetic circuit can be obtained by either controlling the length of the air gaps or the reluctance of the path in the stator iron.

## 1. INTRODUCTION

A permanent magnet alternator is a synchronous generator which has a permanent magnet for its source of magnetization. It is similar to the usual synchronous generator except that instead of the usual rotor winding, it has a permanent magnet rotor. It was first developed in 1940, and is the most popular type of alternator. It is very simple and reliable, and has no brushes or commutator. It is very quiet and has no vibration. It is very efficient and has a high power factor. It is very easy to maintain and has a long life. It is very safe and has no fire hazard. It is very cheap and has a low cost of operation. It is very reliable and has a high efficiency. It is very quiet and has no vibration. It is very efficient and has a high power factor. It is very easy to maintain and has a long life. It is very safe and has no fire hazard. It is very cheap and has a low cost of operation. It is very reliable and has a high efficiency.

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Although the construction of the permanent magnet alternator is simple, it is difficult to manufacture. It is difficult to get the magnet material in the right shape and size. It is difficult to get the magnet material in the right position. It is difficult to get the magnet material in the right quantity. It is difficult to get the magnet material in the right quality. It is difficult to get the magnet material in the right color. It is difficult to get the magnet material in the right texture. It is difficult to get the magnet material in the right taste. It is difficult to get the magnet material in the right smell. It is difficult to get the magnet material in the right sound. It is difficult to get the magnet material in the right touch. It is difficult to get the magnet material in the right feel. It is difficult to get the magnet material in the right look. It is difficult to get the magnet material in the right taste. It is difficult to get the magnet material in the right smell. It is difficult to get the magnet material in the right sound. It is difficult to get the magnet material in the right touch. It is difficult to get the magnet material in the right feel. It is difficult to get the magnet material in the right look.

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In a rotary device such as an alternator, the mechanical system necessary for adjusting the air gap length would be complex, and, in the case of a permanent magnet alternator, would nullify its chief advantage of simplicity.

The alternative method, which consists of controlling the reluctance of the stator iron, is more feasible because such control can be obtained by purely electrical means. If a coil of toroidal form were wound around the hollow cylindrical form of the stator, and a direct current were introduced in this coil, the stator iron would readily be saturated. The effect of saturating the stator iron on the reluctance of the magnetic circuit is not immediately apparent because the flux from the rotor travels in both clockwise and counter-clockwise directions in the stator between adjacent pole faces, whereas the saturation caused by the toroidal winding on the stator is due to flux traveling in but one direction in the stator.

This investigation consists of analysis and experimental verification of the results obtained by toroidal saturation of the stator iron of a permanent magnet alternator. The method of analysis and general results are applicable to all permanent magnet machines, but in order to show to what extent the output voltage can be controlled at various loads and speeds, experimental data for the particular alternator tested was used.

The alternator upon which the analysis and experimental verification were performed is shown in Fig. I. This

In a rotary device such as an alternator, the mechanical system necessary for rotating the armature would be complex, and, in the case of a permanent magnet alternator, would multiply the initial advantages of simplicity.

The alternative method, which consists of controlling the reluctance of the rotor loop, is more feasible because such control can be obtained by purely electrical means. If a coil at constant length were wound around the rotor, electrical form of the rotor, and a direct-current voltage introduced in this coil, one extreme iron would readily be attracted. The effect of saturating the space iron in the reluctance of the magnetic circuit is not necessarily symmetrical because the flux from the rotor travels in both directions and neutralizes direction in the space between adjacent pole faces, whereas the saturation caused by the constant exciting on the rotor is due to flux traveling in but one direction in the space.

This investigation consists of analysis and experimental verification of the results obtained by controlled saturation of the rotor iron of a permanent magnet alternator. The control of magnetic and current circuits are explained in all permanent magnet machines, but in order to save space current the output voltage can be controlled by varying length and space, as mentioned above for the permanent magnet alternator.

The differences upon which the analysis and experimental verification were performed is shown in Fig. 1. This

FIGURE 1  
ALTERNATOR ASSEMBLY







alternator is a four-pole, three-phase, Y-connected machine. Its normal speed is 12,000 RPM corresponding to a frequency of 400 cycles per second. The permanent magnet rotor is of ALNICO VI. Two stators, one of USS Electrical Grade Steel, and one of HIPERNIK, were wound and tested. The stators had shallow slots milled in the outer periphery, one slot opposite each of the eighteen inner slots to admit the toroidal winding, allowing clearance for the stator to be inserted in the housing. The toroidal winding lies in the bottom of the main slots, and the generator windings are placed over the toroidal windings.

Experimental data was obtained from the machine under various conditions of saturation, loading, and speed in order to determine the effects of toroidal saturation upon the output voltage.

alternator is a four-pole, three-phase, Y-connected machine. Its normal speed is 18,000 RPM corresponding to a frequency of 600 cycles per second. The permanent magnet rotor is of ALNICO VI. Two stators, one of 120 Electrical Degree Poles, and one of 180 Electrical Degree Poles, were wound and tested. The stators had similar slots filled in the outer periphery, one also opposite each of the sixteen inner slots to admit the toroidal winding, allowing clearance for the rotor to be inserted in the housing. The toroidal winding lies in the bottom of the main slots, and the generator windings are placed over the toroidal windings. Experimental data was obtained from the machine under various conditions of saturation, loading, and speed in order to determine the effects of toroidal saturation upon the output voltage.

## II. PROCEDURE

The procedure followed has been divided into two separate, but mutually supporting techniques. The first consists of an analytical solution derived from a consideration of magnetic circuit theory as applied to the peculiar magnetic circuit involved. The second procedure consists of experimental determinations of the behavior of a permanent magnet alternator when subjected to the specified conditions of magnetic saturation.

### A. Analytical Procedure

The procedure used to solve the problem of the effect of saturation in the stator iron on the air-gap flux of the permanent magnet in a permanent magnet alternator is graphical in nature. The solution consists of solving two simultaneous equations in which the graphical representation of the flux versus magnetomotive characteristic of the permanent magnet provides one equation, and the flux versus mmf characteristic of the air gaps and stator iron in the magnetic circuit seen by the permanent magnet provides a second equation. The magnetizing force and flux of the permanent magnet must equal the mmf drop and the flux in the external circuit including leakage flux. For the following analysis, hysteresis is neglected so that flux versus mmf characteristics may be represented by single lines.

### Determination of Rotor Characteristic

The characteristics of permanent magnets are represented by a demagnetization curve which is the second



## 11. PROCEDURE

The procedure followed has been divided into two separate, but mutually supporting components. The first consists of an analytical scheme devised from a consideration of magnetic circuit theory as applied to the peculiar magnetic circuit involved. The second procedure consists of experimental determination of the behavior of a permanent magnet alignment when subjected to the specified conditions of magnetic excitation.

### A. Analytical Procedure

The procedure used to solve the problem of the effect of saturation in the rotor iron on the air-gap flux of the permanent magnet in a permanent magnet alignment is graphical in nature. The solution consists of solving the simultaneous equations in which the graphical representation of the flux versus magnetizing characteristic of the permanent magnet provides one equation, and the flux versus magnetizing characteristic of the air gap and rotor iron in the magnetic circuit used by the permanent magnet provides a second equation. The magnetizing force and flux in the permanent magnet must equal the sum drop and the flux in the external circuit including leakage flux. For the following analysis, fluxes are neglected so that flux versus magnetizing force may be represented by single lines.

### Determination of Rotor Characteristics

The characteristics of permanent magnets are represented by a demagnetization curve which is the second



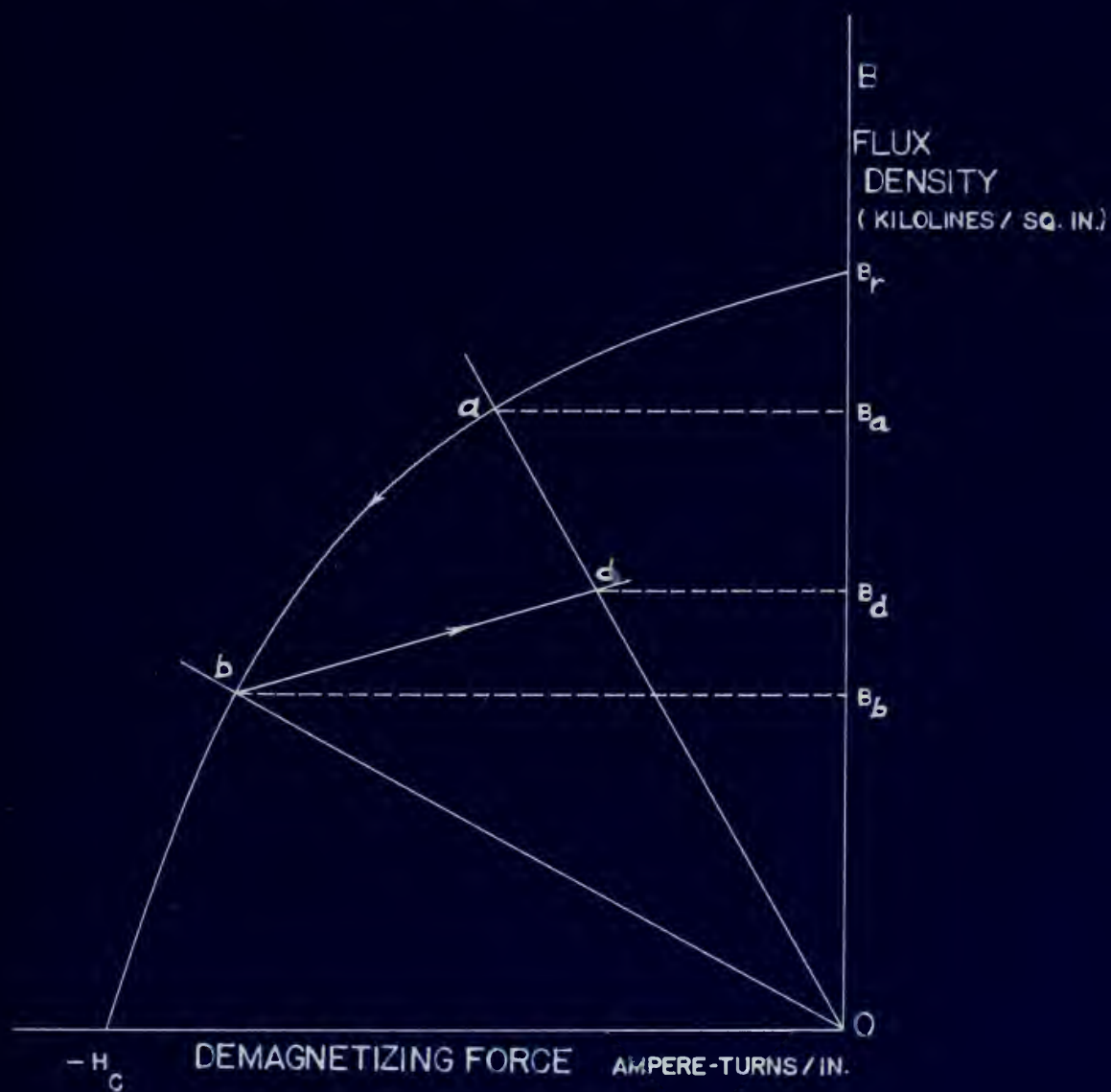
quadrant of the material's hysteresis loop between  $B_r$ , the retentivity, and  $H_c$ , the coercive force as shown in Fig. II. The point  $B_r$  represents the flux density of the magnet when it is magnetically short-circuited; when the magnet is subjected to a demagnetizing force such as an air-gap line  $Oa$ , the point representing the operating condition moves along the demagnetization curve from  $B_r$  to point  $a$ , and  $B_a$  is the flux density in the air gap. If the air gap is increased in length until the air-gap line becomes  $Ob$ , the operating point will move down the <sup>de</sup>magnetization curve from  $a$  to  $b$ , and the resulting flux density will then be  $B_b$ . If the gap is decreased, the operating point will not return along the demagnetization curve, but will travel along a minor hysteresis loop such as  $bd$ . For example, if the air-gap line is again  $Oa$ , the operating point will become point  $d$ , and the flux density becomes  $B_d$ . [1]

In order to determine the characteristics of the permanent magnet rotor, it is necessary to determine the slope of the minor hysteresis loop, otherwise known as the "recovery line", and the position on the demagnetization curve where the recovery line originates. The origin of the recovery line does not necessarily represent the point on the demagnetization curve where the magnetic open-circuit air-gap line intersects the demagnetization curve because the magnet may have been subjected to a demagnetization force in excess of the open-circuit air-gap condition. This would put the open-circuit operating point on the

position of the material is specified from between  $0_{\text{max}}$  and  $0_{\text{min}}$  respectively, and  $H_{\text{max}}$  and  $H_{\text{min}}$  the distance from the origin to the point  $H_{\text{max}}$  respectively the point  $H_{\text{min}}$  of the material. It is assumed that the material is subjected to a homogeneous force such as an air-gap line. On the point representing the operating condition, along the characteristic curve from  $H_{\text{max}}$  to point  $H_{\text{min}}$  and  $0_{\text{max}}$  is the time density in the air-gap. If the air-gap is increased in length with the air-gap line between  $0_{\text{max}}$  and operating point will move down the characteristic curve from  $0_{\text{max}}$  to  $0_{\text{min}}$  and the operating time density will move from  $0_{\text{max}}$  to  $0_{\text{min}}$ . The operating point will not remain the gap is increased, the operating point will not remain along the characteristic curve, but will travel along a shape triangle gap with an  $H_{\text{max}}$  for example, at the air-gap line is again on the operating point will travel from  $0_{\text{max}}$  and the time density between  $0_{\text{max}}$  and  $0_{\text{min}}$ .

In order to determine the characteristics of the permanent magnet motor, it is necessary to determine the stage of the motor hydraulic loop, selected value in the "density line", and the position on the characteristic curve where the density line intersects. The density line does not necessarily represent the point on the characteristic curve where the density intersects the air-gap line between the characteristic curve between the magnet may have been subjected to a homogeneous force the stage of the open-circuit air-gap condition. This would be the open-circuit operating point of the

FIGURE II  
PERMANENT MAGNET BEHAVIOR







intersection of the open-circuit air-gap line and a recovery line whose origin is closer to  $H_c$  on the demagnetization curve (Fig. II). A point on the recovery line of the permanent magnet rotor can be determined by measuring the open-circuit flux per pole with a fluxmeter and plotting this value of flux on the open-circuit air-gap line.

Methods have been devised [2] to determine the open-circuit air-gap line for magnets which do not have a well defined air gap. Scott [3] found that a definite relation exists between the ratio of length-to-diameter of round bar magnets and the flux in the air between poles. This relationship is expressed by a curve of  $B/H$  versus  $l/d$  (Fig. III) where  $B/H$  is the slope of the open-circuit air-gap line, also called the "permeance coefficient", and  $l/d$  is the length-to-diameter ratio of the bar magnet. The relationship holds within a fair degree of accuracy to magnets other than round bar magnets provided that, if the magnet is curved, the poles are not too close together. To apply Scott's bar magnet theory to the multipolar shape of a permanent magnet rotor, an equivalent bar magnet is assumed by estimating the length of the mean flux path between adjacent pole faces to provide the dimension,  $l$  (Fig. IV); an equivalent diameter is established by assuming the pole face of the magnet has the diameter of a circle of the same area as the pole face [3] :

$$d = \sqrt{\frac{4A}{\pi}} \quad (1)$$

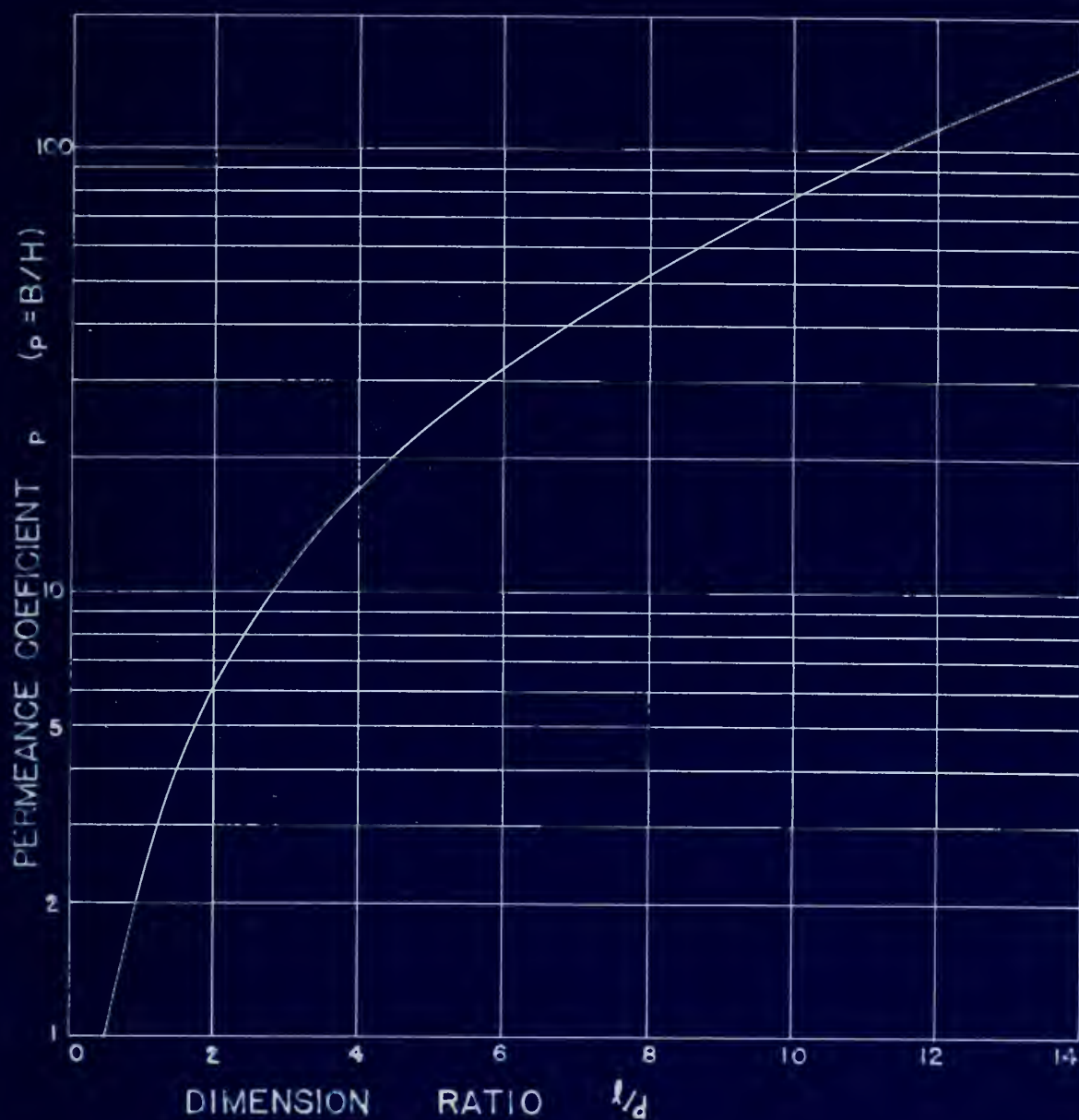
investigation of the open-circuit air-gap line and a  
 necessary line whose origin is placed on the  
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 To apply Scott's bar magnet theory to the reluctance design  
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 measured by estimating the length of the magnet from past  
 between adjacent pole faces to provide the dimension  
 $l$  (Fig. 14); an equivalent diameter is calculated by  
 assuming the pole face of the magnet has the diameter of  
 a circle of the same area as the pole face [3].

$$d = \sqrt{\frac{4A}{\pi}}$$

FIGURE III

PERMEANCE COEFFICIENTS  
OF  
EQUIVALENT BAR MAGNETS







## FIGURE IV

FLUX PATHS IN ROTOR





Having assumed an equivalent  $l/d$ , enter the curve of Fig. III and determine the slope of the open-circuit air-gap line,  $B/H$ . This value of  $B/H$  in conjunction with the measured flux of the magnet establishes the open-circuit operating point of the permanent magnet.

The slope of the recovery line, called the "incremental permeability", can be obtained from manufacturer's literature [4], where the slope of the recovery line is given in the form of a graph of incremental permeability versus the flux density at point of reversal for various magnetic materials. Knowing that the recovery line must pass through the operating point on the open-circuit air-gap line, the slope of the recovery line is determined.

An estimate of the flux versus mmf characteristic for the permanent magnet rotor has now been established. When the rotor is inserted in the stator, the operating point of the magnet will lie on this recovery line. Fig. V shows this flux versus mmf characteristic.

#### Determination of Stator Characteristic

To visualize the approach used to determine the stator characteristic, consider the rotor inserted in the stator. The lines of flux from a magnet pole will cross the air gap and split into two parallel paths in the stator iron and close on themselves through adjacent pole faces. Leakage flux from the permanent magnet will also exist, but this flux does not appear in the stator magnetic circuit and can be considered separately.

having assumed an equivalent  $1/\delta$ , enter the curve of Fig. III and determine the slope of the open-circuit air-gap line,  $5\% \delta$ . This value of  $1/\delta$  is compared with the measured flux of the magnet establishing the open-circuit operating point of the permanent magnet.

The slope of the recovery line, called the "inherent

permeability", can be obtained from manufacturer's

literature [4], where the slope of the recovery line is given in the form of a graph of inherent permeability versus the flux density at point of reversal for various magnetic materials. Knowing that the recovery line must pass through the operating point on the open-circuit air-gap line, the slope of the recovery line is determined.

An estimate of the flux versus magnet characteristic for the permanent magnet rotor has now been established. When the rotor is inserted in the stator, the operating point of the magnet will lie on this recovery line. Fig. 7 shows

this flux versus magnet characteristic.

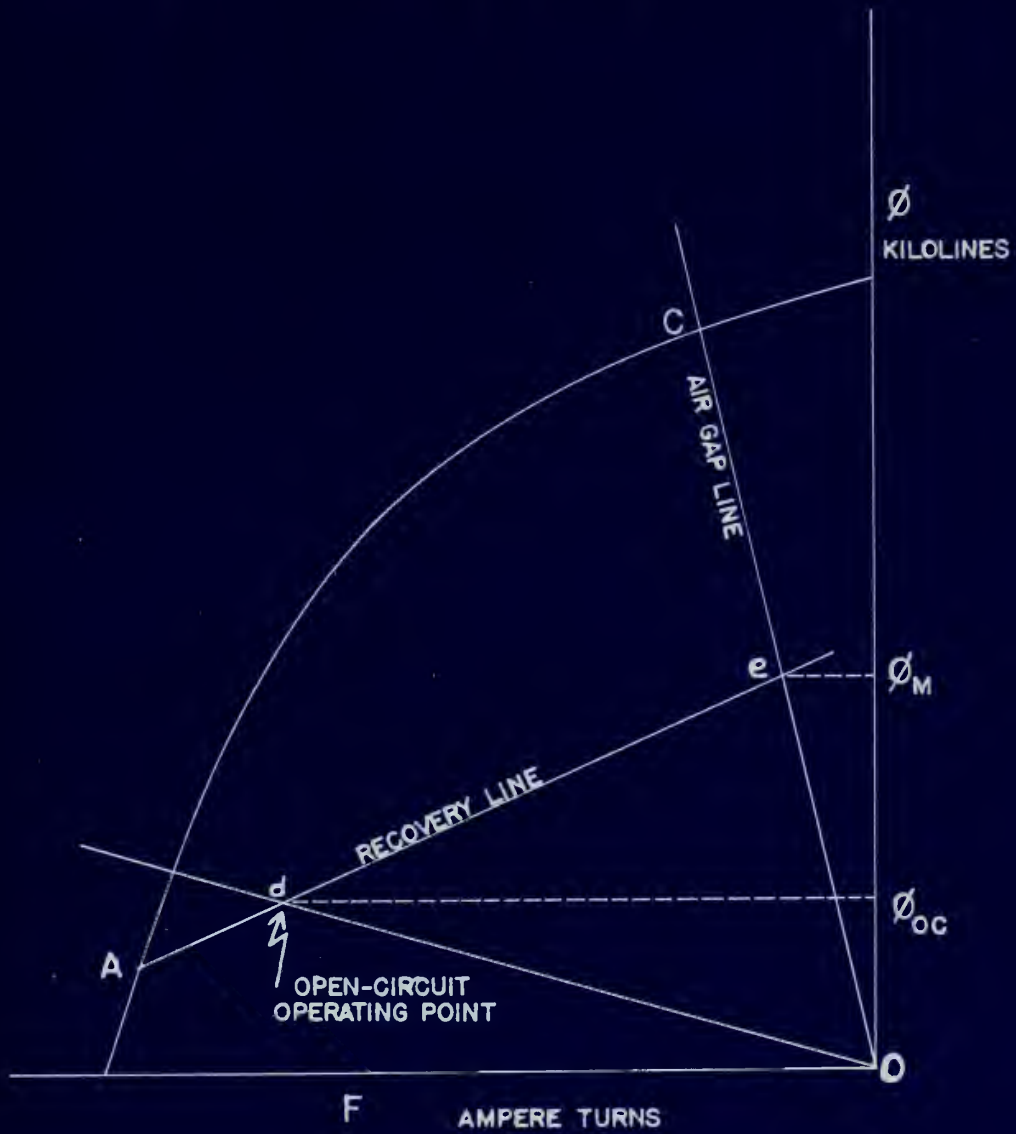
### Determination of Motor Characteristics

To visualize the approach used to determine the motor characteristics, consider the rotor inserted in the stator. The lines of flux from a magnet pole will cross the air gap and split into two parallel paths in the stator iron and close on themselves through adjacent pole faces. Leakage flux from the permanent magnet will also exist, but this flux does not appear in the stator magnetic circuit and can be considered separately.



# FIGURE V

## DETERMINATION OF RECOVERY LINE





Using an electric circuit analogy in which reluctance is analogous to resistance, flux to current, and magnetomotive force to voltage, the magnetic circuit is represented in Fig. VI. The effect of  $R_{\text{(air gap)}}$  can be represented by an air-gap line in the stator characteristic. The effect of  $R_1$  and  $R_2$ , the reluctances of the stator iron paths which are to be saturated by the toroidal winding, can be analyzed separately and added graphically to the air-gap line to obtain the overall magnetic characteristic of the magnetic circuit external to the rotor. Temporarily neglecting the air gap and leakage paths, we now have the analogous circuit shown in Fig. VII. It is to be emphasized that electric circuit analogies are for illustrative purposes only, and that the equations resulting therefrom must always require a graphical solution because of the non-linear nature of reluctance.

Now consider the stator, without the permanent magnet rotor, as a toroid with a continuous winding around it as shown by Fig. VIII. A direct current in the toroidal winding will cause a magnetomotive force between points a and b

$$F_c = F_{ab} = \phi_l R_{ab} \quad (2)$$

where  $R$  is the reluctance and  $F_c$  is the ampere turns in half the toroid. The electric circuit analogy may be represented by Fig. IX.

If the circuit of Fig. IX were cut in half at line

Using an electric circuit analogy in which reluctance

is analogous to resistance, flux to current, and

magnetomotive force to voltage, the magnetic circuit is

represented in Fig. VI. The effect of  $H$  (air gap) can be

represented by an air-gap flux in the series characteristic.

The effect of  $H_1$  and  $H_2$ , the reluctances of the rotor iron

parts which are to be saturated by the rotational winding,

can be analyzed separately and added graphically to the

air-gap flux to obtain the overall magnetic characteristic

of the magnetic circuit equivalent to the rotor. Generally

neglecting the air gap and leakage paths, we may have the

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Now consider the rotor, without air gap and without

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winding will cause a magnetomotive force between points

a and b

$$(2) \quad F_a = F_b = \frac{H_a}{l_a} = \frac{H_b}{l_b}$$

where  $F$  is the pole strength and  $l$  is the mean length in

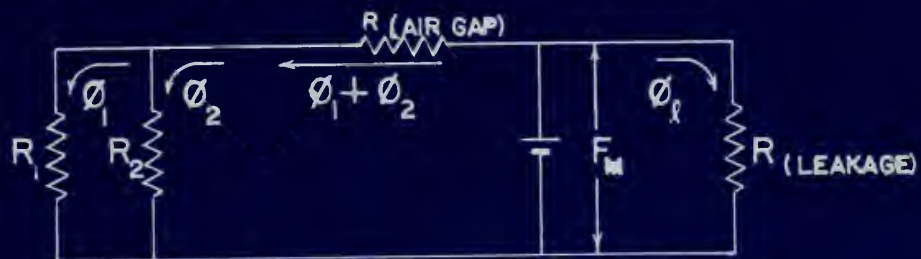
half the toroid. The electric circuit analogy may be

represented by Fig. IX.

If the circuit of Fig. IX were not in half as long



FIGURE VI  
ELECTRIC CIRCUIT ANALOGY



NOTE:  $R_1$  AND  $R_2$  REPRESENT THE RELUCTANCE IN EACH PATH OF THE STATOR IRON

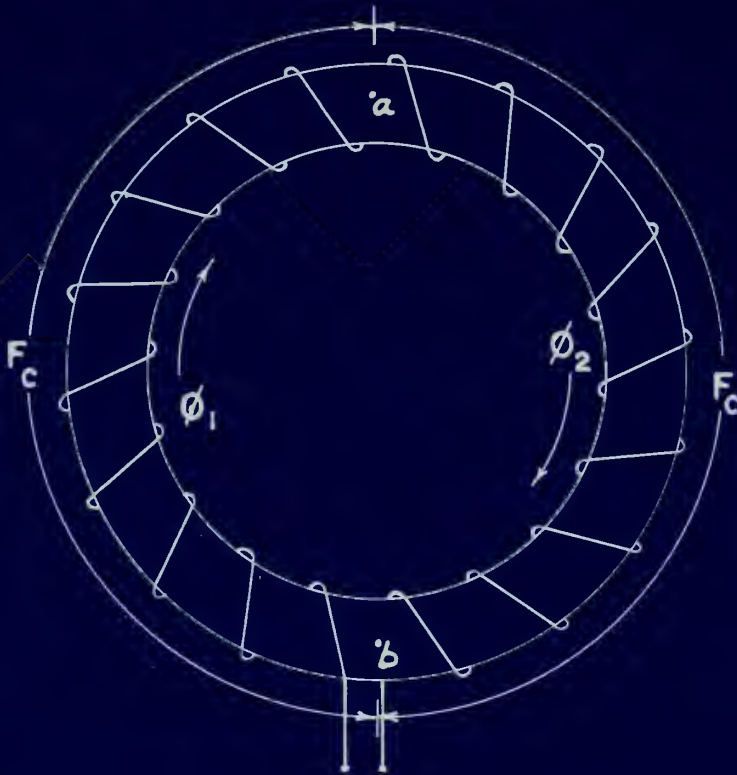
FIGURE VII  
ELECTRIC CIRCUIT ANALOGY OF STATOR  
AIR GAP AND LEAKAGE NEGLECTED





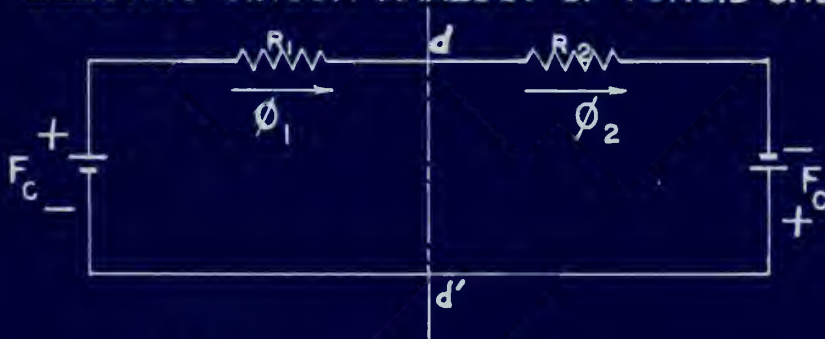
# FIGURE VIII

## TOROIDAL WINDING



# FIGURE IX

## ELECTRIC CIRCUIT ANALOGY OF TOROID ONLY



NOTE:  $F_c = \phi R$





d-d' by a magnetic short-circuit, the flux in each side would be unchanged:

Half of circuit shorted:

$$(1) \quad F_c = \phi_1 R ; \phi_1 = F_c / R ; \text{ shown in Fig. X} \quad (3)$$

Both halves of circuit in series:

$$(2) \quad 2F_c = \phi_1 (2R) ; \phi_1 = F_c / R \text{ as before.} \quad (4)$$

The above case is not to be confused with the case of the curve of  $\phi$  versus  $H$ , where doubling  $H$  (amperes turns per inch) would give, in effect,  $2F$  acting to produce  $\phi$ .

Having established the circuit behavior with no magnet inserted, we can now proceed to find the effect of adding the permanent magnet rotor. For simplicity of illustration, a two-pole magnet is used, but the same conclusions will be valid for multipolar rotors. The effects of the air gap and leakage are still temporarily neglected.

The resulting electric circuit analogy is illustrated by Fig. XI.

The following equations apply:

In left half of the circuit A:

$$(F_c - F_m') = R_a (\phi_1 - \phi_{m1}') = R_a \phi_A \quad (5)$$

In right half of the circuit B:

$$(F_c + F_m) = R_b (\phi_1 + \phi_{m2}') = R_b \phi_B \quad (6)$$

and

$$\phi_m' = (\phi_{m1}' + \phi_{m2}')$$

4-4' by a magnetic short-circuit, the flux in each side

would be unchanged:

Half of circuit shorted:

$$(1) \quad \Phi_0 = \Phi_1 R ; \Phi_1 = \Phi_0 \sqrt{R} ; \text{ same as Fig. 1} \quad (1)$$

Both halves of circuit in series:

$$(2) \quad \Phi_0 = \Phi_1 (2R) ; \Phi_1 = \Phi_0 \sqrt{2R} \text{ as before.} \quad (2)$$

The above case is not to be confused with the case of the

curve of  $\Phi$  versus  $H$ , where doubling  $H$  (square wave form per

turn) would give, in effect, 2X adding to produce  $H$ .

Having established the circuit behavior with no magnet

inserted, we can now proceed to find the effect of adding

the permanent magnet rotor. For simplicity of illustration,

a two-pole magnet is used, but the same conclusions will be

valid for multipole rotors. The effects of the air gap

and leakage are still temporarily neglected.

The resulting electric circuit analogy is illustrated

by Fig. XII.

The following equations apply:

In left half of the circuit is

$$(a) \quad \Phi_0 - \Phi_m = \Phi_1 (R_1 + R_2) = \Phi_1 R_1 \quad (a)$$

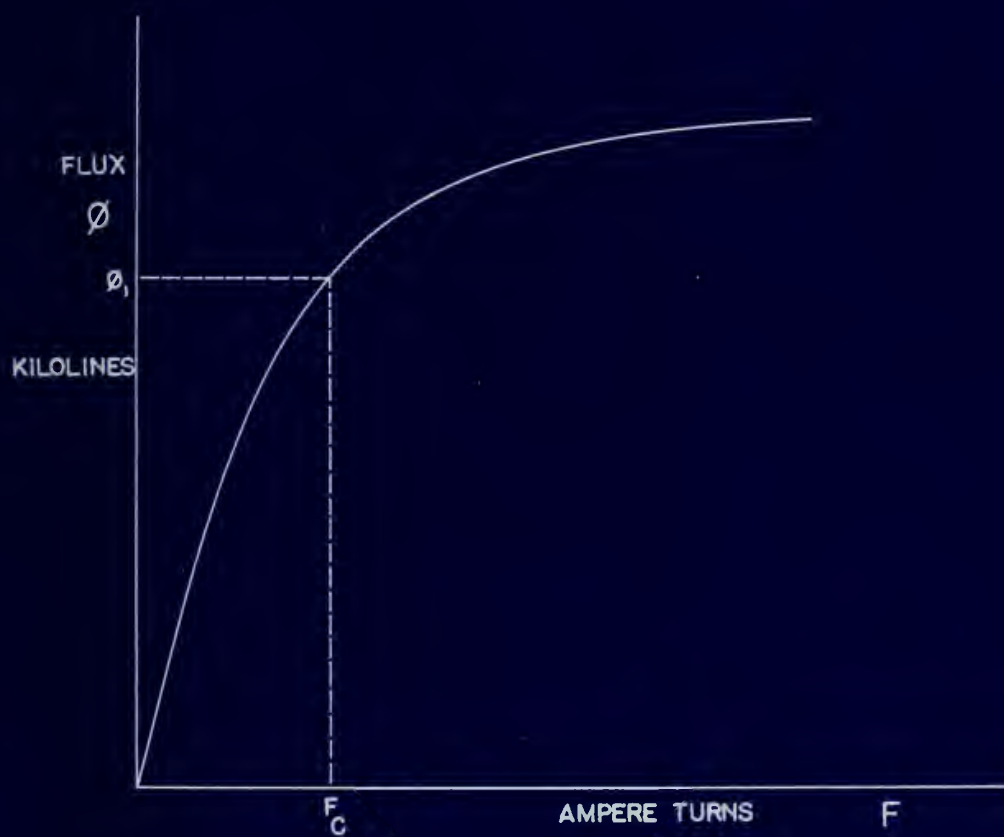
In right half of the circuit is

$$(b) \quad \Phi_0 + \Phi_m = \Phi_2 (R_1 + R_2) = \Phi_2 R_1 \quad (b)$$

$$\Phi_m = \Phi_1 + \Phi_2$$

and

FIGURE X  
DC MAGNETIZATION CURVE —  
IN TERMS OF FLUX AND MAGNETOMOTIVE FORCE







It is also obvious that  $\phi_B - \phi_A = \phi_m'$  (7)

since  $(\phi_1 + \phi_{m1}') - (\phi_1 - \phi_{m2}') = \phi_m' = \text{Flux}$  (8)  
 through the permanent magnet  
 (neglecting leakage effects)

For the actual solution the graphical representation of reluctance (i.e.: the magnetization curve) must be used as shown in Fig. XII.

It now becomes desirable to develop a simple graphical method of expressing  $\phi_m'$  versus  $F_m'$ . In Fig. XIII, consider the point P on the demagnetization curve at  $F_c$  to be the "operating point". Then for each value of  $F_m'$  (the mmf imposed between points ab by the permanent magnet) (see Fig. VIII), add the ordinates  $[(\phi_1 + \phi_{m2}') - \phi_1]$  and  $[\phi_1 - (\phi_1 - \phi_{m1}')] = \phi_{m1}'$  to give the ordinate  $\phi_m'$ . If a new curve is now plotted with the origin taken at P, the result will give a curve of  $\phi_m'$  versus  $F_m'$  as shown in Fig. XIV.

Figure XIV may now be reversed and plotted directly on the demagnetization quadrant of the rotor, sheared\* into the air gap line†, and corrected for leakage‡. The correction for air gap and leakage will yield a curve of  $F$  versus  $\phi_m$ , the same coordinate system as the recovery line. Therefore the point of intersection of these two curves represents the flux through the permanent magnet

---

\* See "Details of Shearing" Appendix A

† See "Calculation of Air Gap Line" Appendix A

‡ See "Estimate of Flux Leakage" Appendix A

(7) It is also obvious that  $\hat{K}_1' = \hat{K}_2' = \hat{K}_3'$

(8) since  $(\hat{K}_1' + \hat{K}_2') - (\hat{K}_1' - \hat{K}_2') = \hat{K}_3' = \hat{K}_4'$

through the subsequent stages

(excluding boundary stages)

For the natural solution the corresponding representation of reference (1.9.1) the corresponding curve must be used as shown in Fig. III.

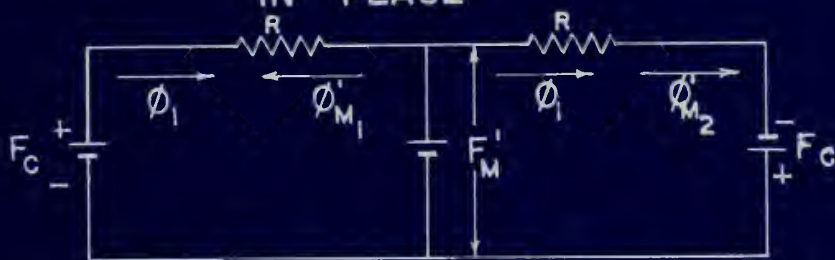
It now becomes desirable to develop a simple algorithm method of expressing  $\hat{K}_n'$  versus  $\hat{K}_1'$ . In Fig. III, consider the point P on the denormalization curve as  $\hat{K}_1'$  so on the "operating point". Then for each value of  $\hat{K}_1'$  (the unit imposed between points as by the subsequent stages) (see Fig. VIII), add the equivalent  $[(\hat{K}_1' + \hat{K}_2') - \hat{K}_1']$  and  $[(\hat{K}_1' - \hat{K}_2') - \hat{K}_1']$  to give the equivalent  $\hat{K}_n'$ . In a new curve is now plotted with the origin taken as P, the results will give a curve of  $\hat{K}_n'$  versus  $\hat{K}_1'$  as shown in Fig. XIV.

Figure XIV may now be reversed and plotted directly on the denormalization graph and of the major, minor, into the air gap line<sup>†</sup>, and converted the results. The correction for air gap and pressure will yield a curve of P versus  $\hat{K}_n'$ , the same equivalent states as the boundary line. Therefore the plot of denormalization of some two curves represents the line through the subsequent stages

† See "Details of Working Assumptions" and "Calculation of Air Gap Line" Appendix A  
 ‡ See "Estimate of Peak Pressure" Appendix A

# FIGURE XI

## ELECTRIC CIRCUIT ANALOGY WITH ROTOR IN PLACE



NOTE:  $F'_M$  IS THE MMF IMPOSED BETWEEN THE POINTS  
a-b OF THE STATOR

## FIGURE XII GRAPHICAL SOLUTION FOR $\phi'_M$

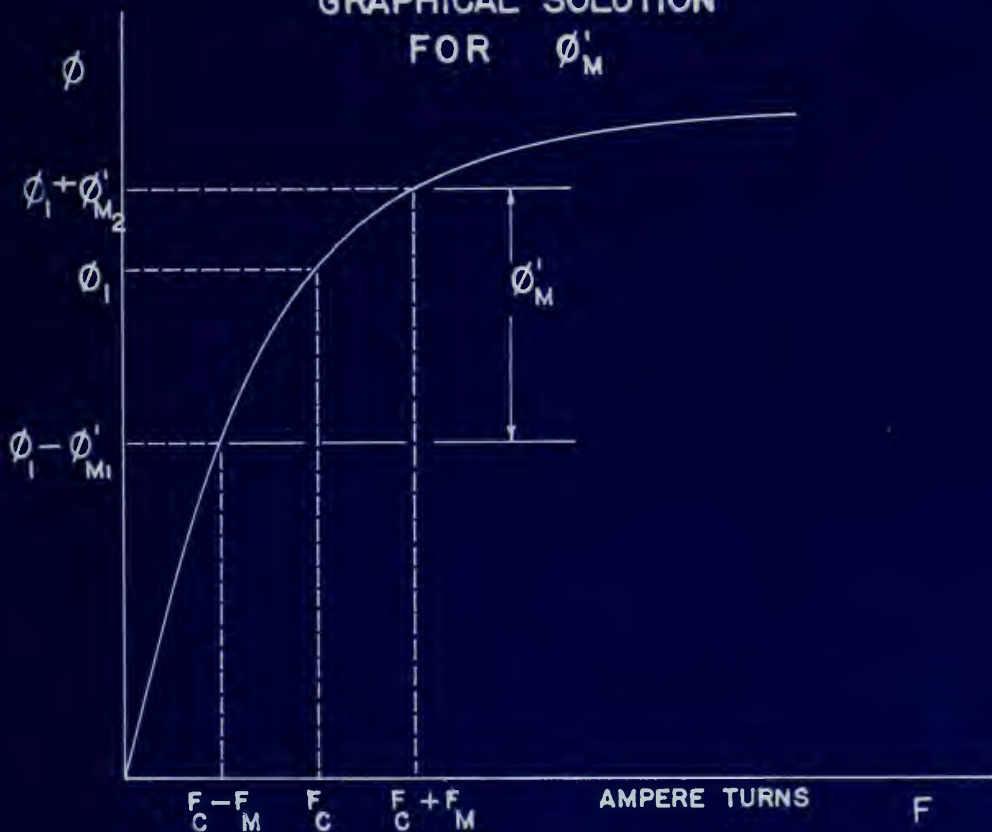
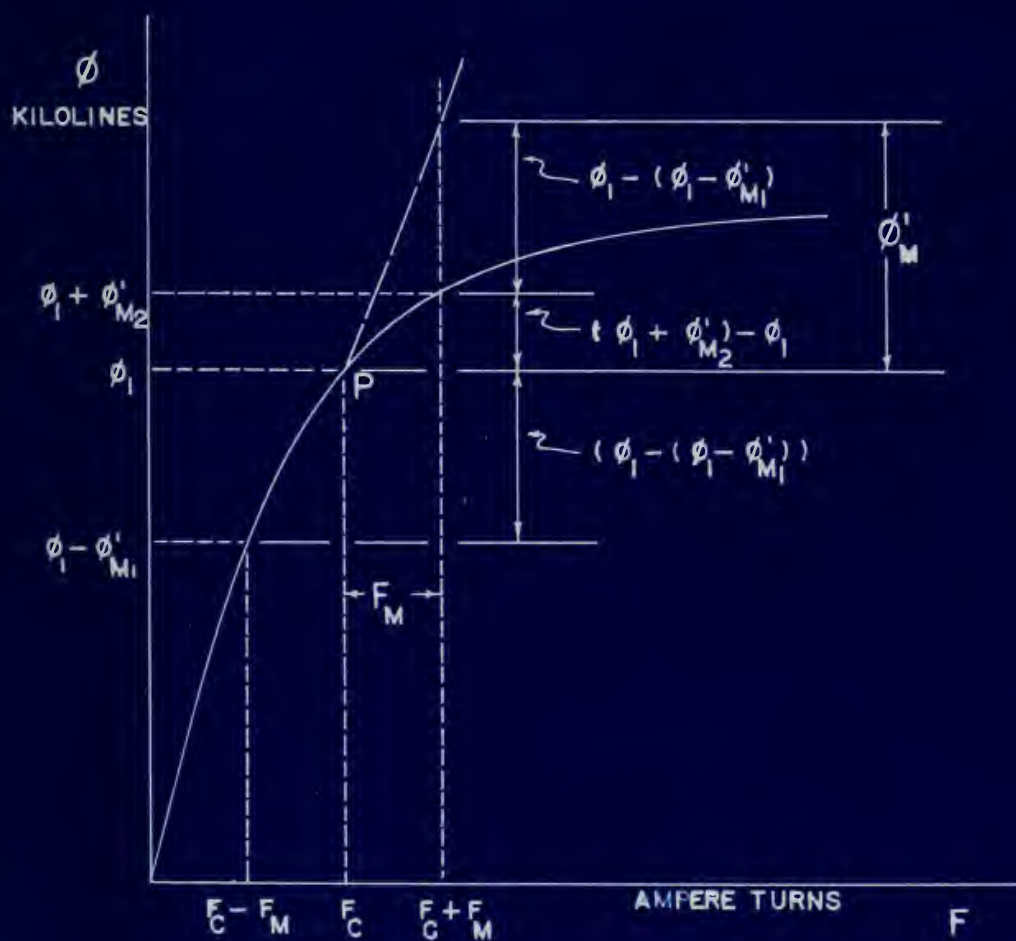






FIGURE XIII  
GRAPHICAL SOLUTION

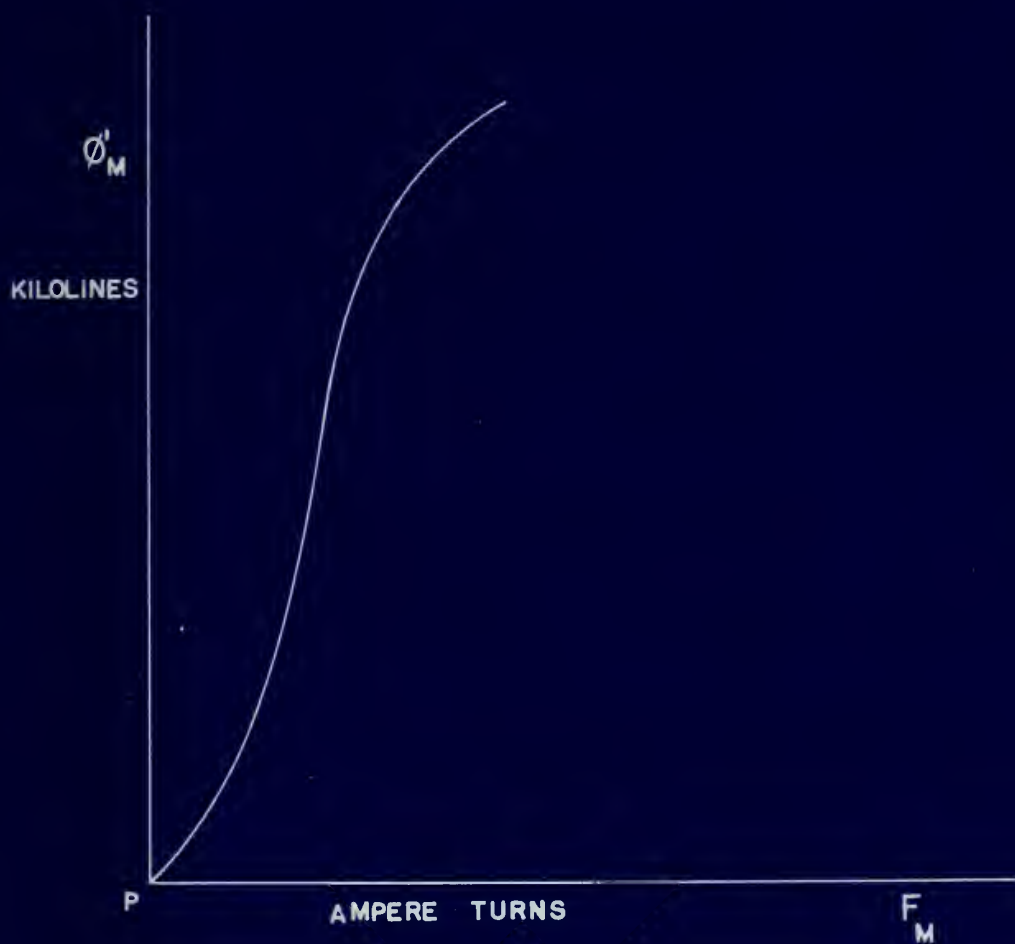






# FIGURE XIV

$\phi'_M$  VS.  $F_M$  CURVE





under existing conditions. Because of the nearly vertical slope of the  $\phi_m'$  curve, the leakage correction is small and negligible error is introduced, percentage wise, by neglecting it. Therefore the  $\phi_m'$  versus  $F_m$  curve may be used for the solution of the simultaneous (graphical) equations of the magnetic circuit.

The leakage is estimated as a function of magnetic potential drop in the circuit, and is assumed to be linear\*. It is shown as line OL on Fig. XV. The effect of this leakage is to reduce the useful flux, and therefore at any value of  $F$  or  $U$  (magnetic potential drop in ampere turns), the leakage flux must be subtracted from the magnet flux, to give the useful flux. This can be shown as having the same effect as a change in the slope of the recovery line of the magnet would have, and the results may be shown as a "virtual recovery line" on Fig. XV. The intersection of the reversed  $\phi_m$  versus  $F_m$  curve with the "virtual recovery line" will now provide a solution for the state of useful flux in the air gap.

Furthermore it is readily seen that as the direct current in the toroidal winding is varied, ( $F_c$  is varied), the shape of the  $\phi_m$  versus  $F_m$  curve changes as shown in Fig. XVI.

Hence when these curves are reversed and plotted on the demagnetization curve as before, and corrected for the air

---

\* See "Estimate of Flux Leakage" Appendix A



under existing conditions. Because of the highly variable slope of the  $\frac{1}{2}$  curve, the leakage correction is small and negligible error is introduced, particularly when, as suggested in Figure 11, the  $\frac{1}{2}$  curve is used for the solution of the simultaneous (geological) equations of the magnetic circuit.

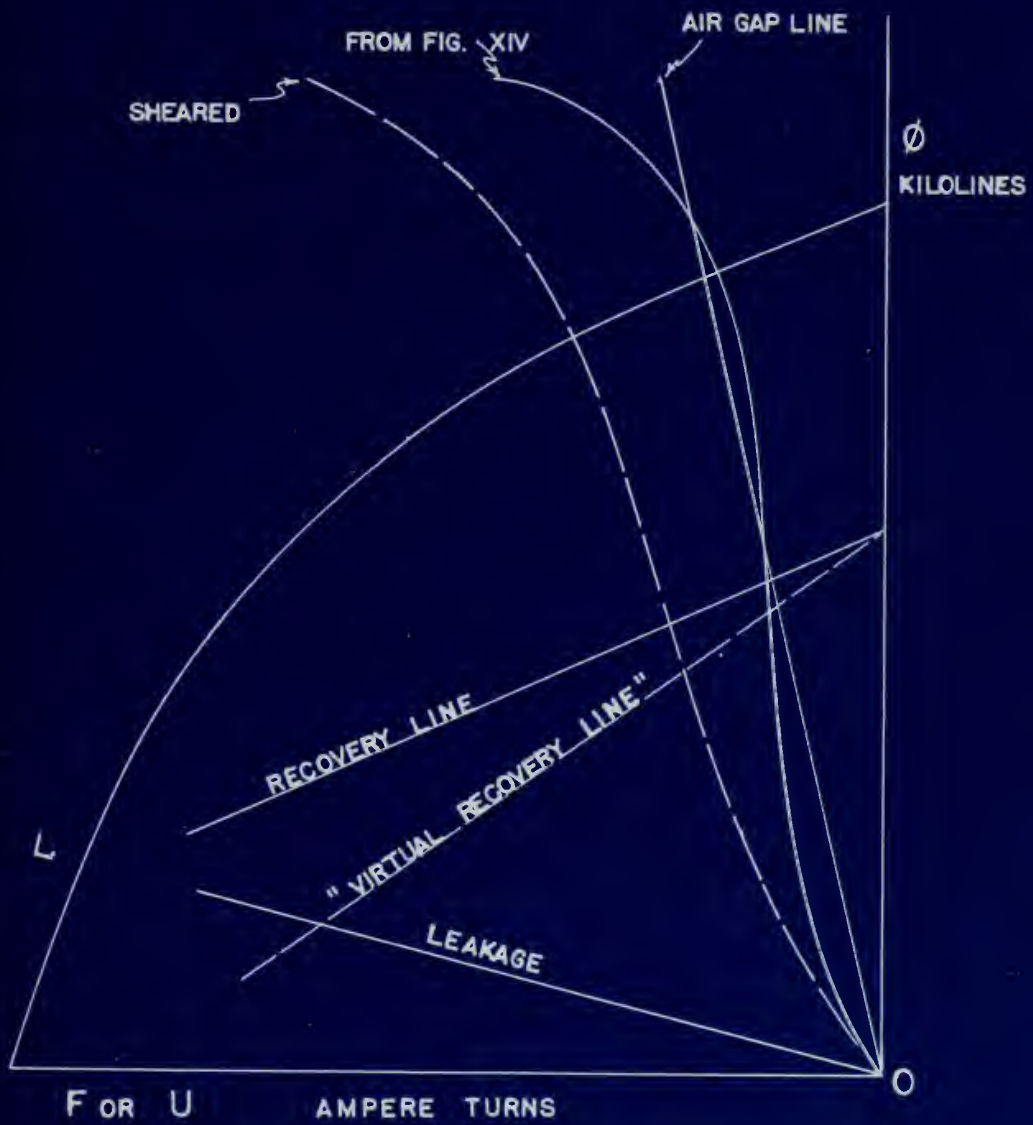
The leakage is estimated as a function of magnetic potential drop in the circuit, and is assumed to be linear.\* It is shown as line DE on Fig. IV. The effect of this leakage is to reduce the useful flux, and therefore as the value of  $\phi$  or  $B$  (magnetic potential drop in magnetic circuit) the leakage flux must be subtracted from the useful flux, to give the useful flux. This can be done as shown in Figure 12, and effect as a change in the slope of the secondary line of the magnet would have, and the result may be shown as a "virtual recovery line" on Fig. IV. The relationship of the reversed  $\frac{1}{2}$  curve with the "virtual recovery line" will now provide a solution for the value of useful flux in the air gap.

Furthermore it is readily seen that as the circuit current in the circuit winding is varied, ( $\phi$  is varied) the slope of the  $\frac{1}{2}$  curve varies, and shown in Fig. XVI.

When both lines are reversed and plotted on the same graph, the result is shown, and corrected for the air

# FIGURE XV

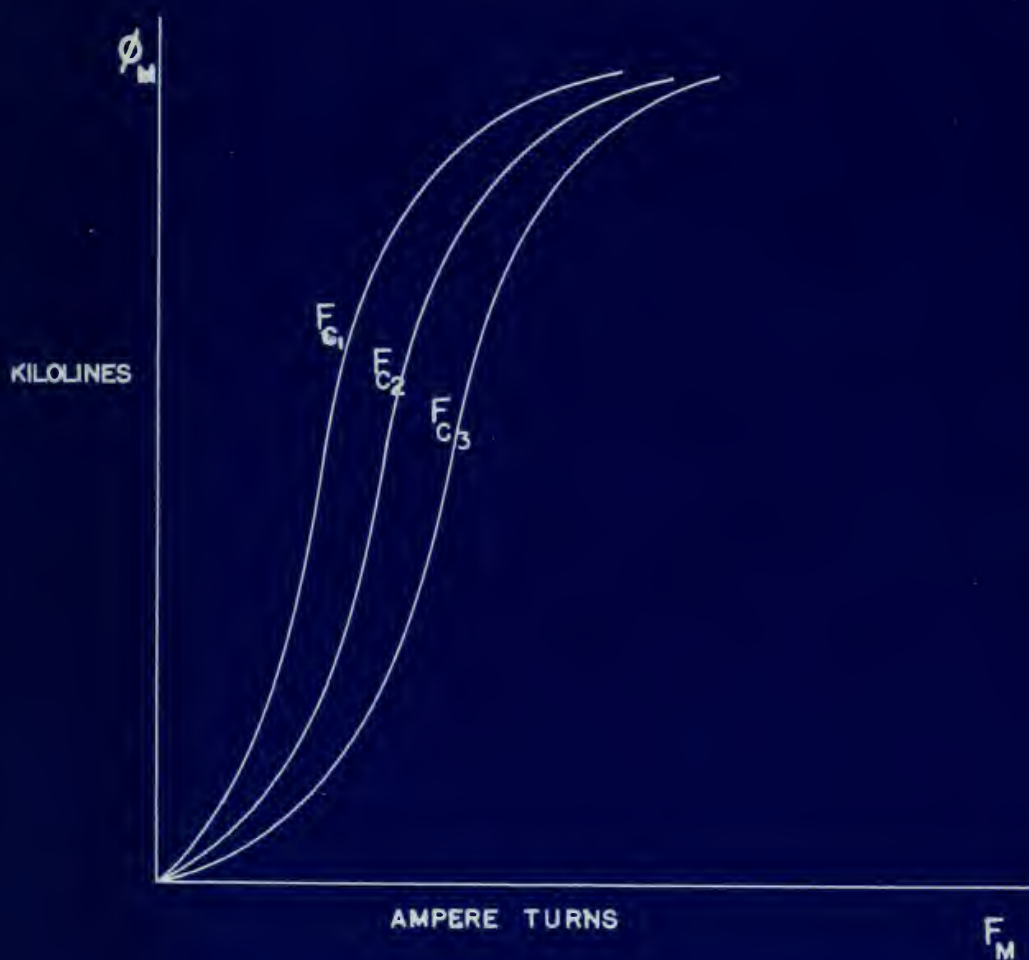
## CIRCUIT CHARACTERISTICS PLOTTED ON MAGNET CHARACTERISTICS





## FIGURE XVI

EFFECT OF  $F_C$  ON THE  $\phi'_M$  VS.  $F_M$  CURVE







gap, the intersection with the "virtual recovery line" moves progressively toward the left, as shown in Fig. XVII, and the effective air gap flux  $\phi_g$  is thereby decreased.

If the alternator is running at constant speed, a common occurrence in synchronous machines, the voltage output will be directly proportional to the useful gap flux  $\phi_g$ , and we have therefore established a method of control over the output voltage of a permanent magnet alternator.

#### B. Experimental Procedure

In order to verify the effectiveness of controlling a permanent magnet alternator by saturation of the stator iron, two stators, one of USS Electrical Grade Steel, and one of HIPERNIK were wound with coils of toroidal form, in addition to the normal three-phase winding. Tests of performance were made under varying conditions of saturation, loading and speed. The data obtained was correlated in a series of graphs illustrating the characteristics of this type of voltage control.

The load circuit used for testing the permanent magnet alternator consisted of a three-phase, y-connected, balanced load.

A Ward-Leonard system prime mover driving the alternator through a 1.5:10 V-belt drive was found to be the most effective means for maintaining constant alternator speeds. No synchronous drive of usable size was available; moreover, a synchronous drive would limit the test frequency to but one value.

Fig. 2. Installation with the "Virtual Power Line" moves progressively toward the left, as shown in Fig. 2, VII, and the effective air line  $V_0$  is thereby decreased. If the elevator is lowered at constant speed, a constant resistance is experienced in the system. The system output will be directly proportional to the weight of the  $V_0$  and we have therefore established a method of control over the output voltage of a permanent magnet generator.

### II. Experimental Procedure

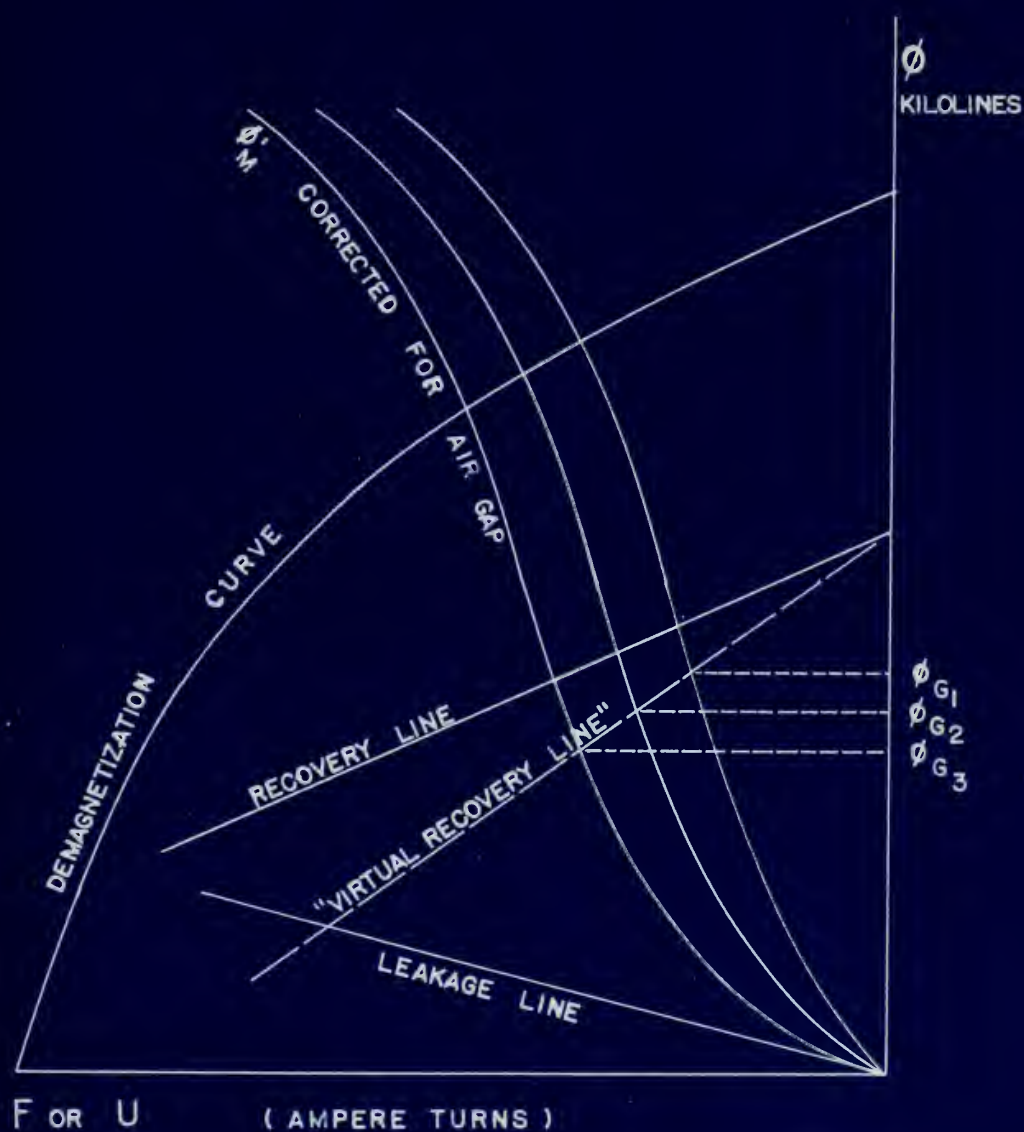
In order to verify the effectiveness of controlling a permanent magnet generator by variation of the output, two systems, one of the Electrical Power System, and one of the HILITEK were used with coils of constant force, in addition to the normal three-phase winding. Tests of performance were made under varying conditions of excitation, loading and speed. The data obtained was correlated in a series of graphs illustrating the characteristics of this type of voltage control.

The load circuit used for testing the permanent magnet generator consisted of a three-phase, Y-connected, balanced load.

A Ward-Leonard system drive system driving the generator through a 1.510 T-bolt drive was found to be the most effective means for maintaining constant generator speed. No synchronous drive of variable speed was available; moreover, a synchronous drive would limit the speed frequency to but one value.

# FIGURE XVII

EFFECT OF  $F_c$  ON AIR GAP FLUX







The frequency for each test was set by maintaining a Lissajou pattern on an oscilloscope, an oscillator being used to measure the frequency.

The ~~load~~ resistance were slide-wire rheostats which were balanced at various values of resistance with a calibrated ohmmeter. In the tests where an inductive load was used, standard 100 millihenry inductances were connected in series with slide-wire rheostats so that the resistive part of the load could be balanced also.

Data was taken at given constant frequencies and load resistances. Control current was varied from 0 to 8 amperes in one ampere steps; at each value of control current, the generator load current and terminal voltage were read on rms-reading thermocouple instruments. The data recorded was direct-current control current, alternating-current terminal voltage, and alternating-current load current.

From the load current measured, the alternating-current real power was computed by the equation:

$$P = 3I^2R_L \quad (9)$$

Otherwise, the data taken was used directly in plotting the curves showing the results.

The results obtained from tests on the USS Electrical Grade stator are of limited value because it was found that the toroidal control winding developed multiple grounds when the stator was inserted in the stator housing. Because



The frequency for each test was set by maintaining a  
 constant power on an oscilloscope, an oscilloscope being  
 used to measure the frequency.

The load resistance was varied with the frequency and  
 were balanced at various values of resistance with a  
 calibrated capacitor. In the test where an inductive load  
 was used, standard 100 millihenry capacitors were connected  
 in series with the load to compensate for the inductive  
 part of the load could be balanced also.

Load was varied at given constant frequencies and load  
 resistance. Control current was varied from 0 to 2  
 amperes in one ampere steps; at each value of control  
 current, the generator load current and terminal voltage  
 were read on two reading instruments. The  
 data recorded was direct-current control current, alternating-  
 current terminal voltage, and alternating-current load  
 current.

From the load current measured, the alternating-current  
 real power was computed by the equation:

$$(2) \quad P = I_L^2 R_L$$

Otherwise, the data taken was used directly in plotting the  
 curves showing the results.

The results obtained from tests on the two generators  
 were plotted and of limited value because it was found that  
 the terminal control voltage varied with the frequency  
 when the motor was connected in the motor circuit. Because

of these grounds, the ampere-turns of control mmf could not be established and no control current-terminal voltage relationship could be established. Nevertheless, current in the control winding had a definite effect on the generator terminal voltage.

Usable results were obtained from the HIPERNIK stator.

A summary of the test conditions for the tests on the HIPERNIK stator are as follows:

Frequency (cycles per second)	400	350	300
Load Resistance (ohms per phase)	open circuit 46.5 93.0 139.5	open circuit 46.5 93.0 139.5	open circuit 46.5 93.0 139.5
Inductive Load (per phase)	100 mh + 100 ohms	100 mh + 100 ohms	100 mh + 100 ohms

Tests on the HIPERNIK stator with an auxiliary flux leakage path were made. The auxiliary leakage path consisted of HIPERNIK discs clamped to each end of the rotor, but separated from the rotor by non-magnetic TEFLON spacers:

No. of 0.01" TEFLON spacers	2	2	2
No. of 0.014" HIPERNIK discs	1	2	2
Frequency in cps	400	400	350
Load in ohms/phase	open circuit 100	open circuit 100	open circuit 100





### III. RESULTS

Experiment and analysis establish the following results:

1. The generator terminal voltage can be reduced, by means of the control winding, to a smaller value than the terminal voltage before control current is applied to the control winding. This reduction is caused in part by an actual reduction in flux from the magnet, and in part by an increase in the portion of magnet flux that traverses the leakage paths.
2. The percent of voltage control is directly dependent on the flux leakage path seen by the permanent magnet rotor.
3. The percent voltage reduction of item (1) is independent of the generator load current and power factor of the current, although the magnitude of voltage reduction is proportional to the initial voltage.
4. The relation between control current and terminal voltage is linear, provided the leakage paths do not saturate:

$$E = E_1 - KI_{dc} \quad \text{or} \quad \phi = \phi_1 - KI_{dc} \quad (10)$$

5. The wave shape of the terminal voltage is not affected, except in amplitude, by the saturation of the stator iron by the control current, provided the stator is designed so that harmonics are negligible. In the USS Electrical stator, which was designed with a slot skew, no harmonics were noticeable on the oscilloscope and the wave shape was not noticeably affected by saturation. In the

Regulation and automatic control of the generator

1. The generator automatic voltage regulator is designed to maintain the terminal voltage of the generator constant, in a certain range, when the load varies. This is achieved by varying the field current. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage.

2. The method of voltage control is directly dependent on the type of generator. For a synchronous generator, the voltage is controlled by varying the field current. For an asynchronous generator, the voltage is controlled by varying the load. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage.

3. The relation between terminal voltage and load is linear, provided the load is not too large. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage.

4. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage.

$$(10) \quad E = E_1 - I_a R_a = E_1 - I_a R_a$$

5. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage. The voltage regulation is defined as the ratio of the change in terminal voltage to the no-load terminal voltage, expressed as a percentage.



HIPERNIK stator which, for reasons of economy, was constructed with straight slots, some effects on harmonics due to stator saturation were noticed.

6. The magnetic material of the stator has negligible effect on voltage control providing the material is magnetically soft and is unsaturated when no control current is applied.

7. There is no net voltage induced in the toroidal winding by the air gap flux.

...the fact that the ...  
...the fact that the ...  
...the fact that the ...  
...the fact that the ...  
...the fact that the ...

#### IV. DISCUSSION OF RESULTS

The two stators were wound and tested in order to determine the effect of different magnetic materials on the regulation of the generator output voltage when controlled by a direct-current toroidal winding. The four-pole Alnico VI permanent magnet rotor, the cast aluminum stator housing, and the two stators are illustrated in Fig. I. The detailed drawings of the stator and rotor appear in Fig. XX.

The generator prime mover consisted of a direct current motor, supplied from a direct current motor-generator set with field control. Frequency of alternator voltage was continuously checked by means of an oscilloscope.

Tests were performed under balanced resistive loads from no load to heavy loads, and one test was performed under a lagging reactive load of 0.37 power factor. Tests were conducted at 400, 350, and 300 cycles per second.

The first stator tested was of USS Electrical Grade Steel with a direct-current toroidal control winding of 162 turns of 24 gauge wire. This stator had a slot skew of one slot pitch. However this stator was found to have multiple grounds in the toroidal winding, and therefore the data must be considered of limited value. The second stator was of HIPERNIK with a toroidal winding of 198 turns of 24 gauge wire. Appendix A gives the details of the generating windings, and the magnetic properties of USS Electrical Grade Steel and HIPERNIK are given in Appendix B.

For the particular HIPERNIK stator tested, it was found



#### IV. DISCUSSION OF RESULTS

The two stages were found and tested in order to determine the effect of different magnetic materials on the regulation of the generator output voltage and speed. The two-stage system by a direct-current control winding. The two-stage system VI presents a new type, the new design system. The two stages are illustrated in Fig. 1. The detailed drawings of the system and motor system in Fig. 2. The generator system was connected to a direct-current motor, supplied from a direct-current motor-generator set with field control. The generator system was continuously changed by means of an electromagnet. Tests were performed under balanced conditions. Tests from no load to heavy loads, and the test was performed under a lagging reactive load at 0.75 power factor. Tests were conducted at 400, 500, and 600 rpm per second. The first stage tested was of the electrical type. Speed with a direct-current control winding of 100 turns of 24 gauge wire. This stage had a slip of one slip. However this speed was found to have multiple grounds in the control winding, and therefore the data must be considered of limited value. The second stage was of the electrical type with a control winding of 120 turns of 24 gauge wire. According to the design of the generator winding, and the magnetic properties of the electrical stage and electrical motor system, it was found for the generator electrical motor system, it was found

that the generator terminal voltage for a given load could be reduced to 63 per cent of its initial value by applying direct current to the toroidal control winding. Further control could have been obtained by applying larger amounts of control current at the expense of increased  $I^2R$  losses in the control winding. The final limitation on the amount of control is that the permanent magnet rotor should not be subjected to a knockdown lower than the existing knockdown point on its demagnetization curve.

Considering the expression for generated voltage:

$$E = K \phi n \quad (11)$$

and assuming the terminal voltage of the generator at a given load is to be held constant, then:

$$\phi n = K' \quad (12)$$

and the relation between  $\phi$  and  $n$  must be a hyperbola. The speed of the generator can vary along the hyperbola within certain limits, determined by the amount  $\phi$  can be changed by the control winding, and yet maintain a constant terminal voltage.

The relation between the control current  $I_c$  and the effective air gap flux  $\phi$  is nearly a straight line with negative slope. (See Fig. XXVIII). Within a limited range, the flux may be considered to vary inversely with a control current.

$$\phi = \frac{K}{I_c} \quad (13)$$





Therefore at constant terminal voltage,

$$\phi_n = K'' \quad (14)$$

$$\frac{n}{I_c} = K''' \quad (15)$$

$$\text{or } n = K'''' I_c \quad (16)$$

and the relation between speed (or frequency) and control current may be seen to be a straight line. This is borne out by the experimental results. (See Fig. XXXVIII).

Since  $\phi$  decreases linearly with control current, and the power dissipated in the control winding increases as the square of the control current, it is seen that the range of voltage control obtained is limited by increased power consumption in the control winding.

The linear relation between control current and terminal voltage can be explained by consideration of the graphical solution of the problem. It is found that control current moves the characteristic of the stator, ( $\phi'_m$  in Figure XIV), an equal amount to the right for each unit increase in control current. Since the point of intersection of the  $\phi'_m$  curve and the permanent magnet recovery line occurs in the linear region of the  $\phi'_m$  curve, the point of intersection follows a linear relation.

Analytically it can be seen by expressing the linear portion of the  $\phi'_m$  curve as:

$$\phi'_m = aF - b I_{dc} \quad (17)$$

$$(14) \quad \dot{V}_m = E_m$$

$$(15) \quad \frac{E_m}{I_m} = \frac{E}{I}$$

$$(16) \quad \dot{V}_m = E_m I_m$$

and the relation between speed (or frequency) and control current may be seen to be a straight line. This is shown one by the experimental results. (See Fig. XXVIII).

Since  $\dot{V}_m$  decreases linearly with control current, and the power dissipated in the control winding increases as the square of the control current, it is seen that the range of voltage control obtained is limited by increasing power consumption in the control winding.

The linear relation between control current and terminal voltage can be explained by consideration of the graphical solution of the problem. It is found that control current moves the characteristic of the motor, ( $\dot{V}_m$  in Figure XIV), an equal amount to the right for each unit increase in control current. Since the point of intersection of the  $\dot{V}_m$  curve and the terminal voltage property line occurs in the linear region of the  $\dot{V}_m$  curve, the point of intersection follows a linear relation.

Analytically it can be seen by expressing the linear portion of the  $\dot{V}_m$  curve as

$$(17) \quad \dot{V}_m = aI + b$$



The "virtual" permanent magnet recovery line may be expressed as:

$$\phi_{\text{gap}} = C - dF \quad (18)$$

Figure XVIII shows these expressions in graphical form plotted on conventional coordinates.

Solving for  $\phi_g$ :

$$\phi_g = A - B I_{dc} \quad \text{or} \quad \phi_g = \phi_1 - k I_{dc} \quad (19)$$

For any initial value of  $\phi_1$  for a given load, the above expression for  $\phi_g$  holds, thus the per cent reduction of the initial voltage is independent of the load current drawn.

If the generator were driven by a constant speed drive, it is possible to maintain a constant terminal voltage from no load to full load by means of the control winding.

Moreover, if the power for the control winding were to be obtained from the generated output, the control power would be least when the power demand on the generator were the greatest. (See Fig. XXXVI). That the amounts of control power required for certain applications is practical is indicated by Figs. XXXVI and XXXVII, in which the control winding is used to maintain constant terminal voltage for (1) variable power consumption by the load, and (2) variable generator speed from 9,000 RPM to 12,000 RPM.

The control of terminal voltage under all load conditions, and with variations in prime mover speed appears

$$(12) \quad \dot{V}_{\text{reg}} = 0 - \dot{V}_f$$

Figure XVII shows power regulation in frequency form

adjusted in conventional coordinates.

Setting for  $\dot{V}_f$

$$(13) \quad \dot{V}_f = \dot{V}_A - \dot{V}_T \text{ or } \dot{V}_f = \dot{V}_A - \dot{V}_T$$

For any instant value of  $\dot{V}_f$ , the given load, the above expression for  $\dot{V}_f$  holds, and the per cent regulation of the virtual voltage is independent of the load current.

If the generator were driven by a constant speed drive, it is possible to maintain a constant terminal voltage from no load to full load by means of the control winding.

However, if the power for the control winding were to be obtained from the generator output, the control power would be taken from the first stage in the generator and the

power required for certain amplification is provided in indicated by Figs. XXVI and XXVII. In which the control winding is used to maintain constant terminal voltage for

(1) variable power consumption by the load, and (2)

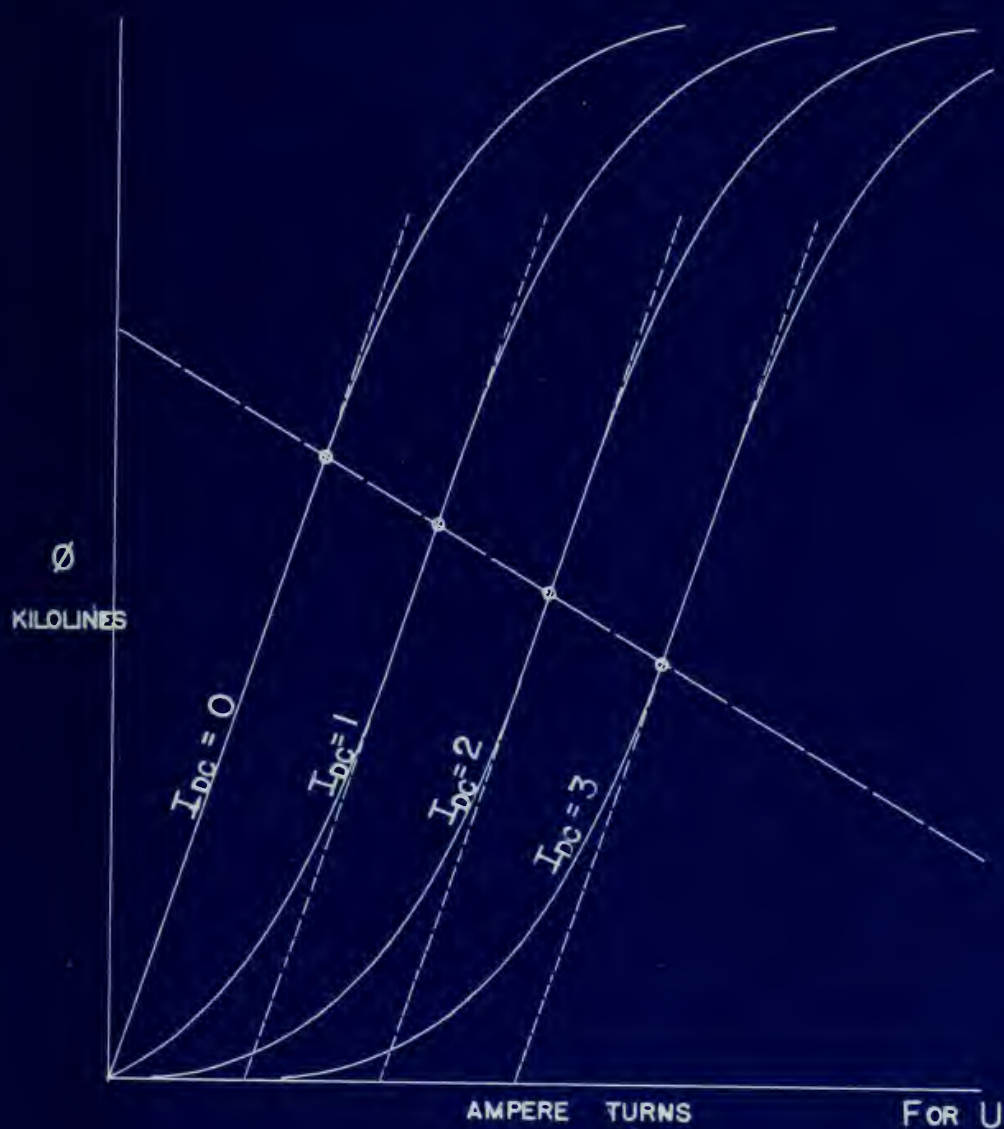
variable generator speed from 0.95 to 1.05 p.u.

The control of terminal voltage under all load

conditions, and with variation in prime mover speed appears



FIGURE XVIII  
GRAPHICAL SOLUTION





to be a highly valuable feature and should find wide application in systems which can use permanent magnet generators to advantage. Since the control is by purely electrical means, automatic voltage regulation is feasible.

The wave shape of the terminal voltage of a properly designed stator appears to remain constant, except in amplitude, throughout the range of control current used. Observations were made on an oscilloscope so minor changes in shape may not have been discerned. The saturation of the stator by control current does not have any effect on the stator teeth since all flux induced by the toroidal control winding must be contained within the toroid; thus, the condition of the iron in the stator teeth immediately opposite the permanent magnet poles is unchanged by control current. The air gap in the generator was only 0.007" so little air gap flux redistribution results as the control current increases. For these reasons, the effect of saturation of the stator iron will not have as much effect on the voltage wave shape as might first be suspected. On a machine with a larger air gap, some variation in the output voltage wave shape might well be observed.

Analysis and experiment both indicate that the stator magnetic material has little effect on the voltage control. This is because the point of intersection of the stator magnetic characteristic curve and the permanent magnet characteristic in the graphical solution occurs in the non-saturated region of the stator characteristic. That is,

to be a slightly variable function and should find wide  
 application in systems which use the permanent magnet  
 generator as a reference. Since the control is by purely  
 electrical means, automatic voltage regulation is feasible.  
 The wave shape of the terminal voltage of a properly  
 designed motor appears to remain constant, except in  
 amplified, throughout the range of limited current used.  
 Disturbances were made as an over-voltage as minor changes  
 in shape may not have been detected. The regulation of the  
 motor by control current does not have any effect on the  
 motor load since all that is done by the terminal control  
 winding may be obtained within the motor; hence, the  
 condition of the iron in the motor does not immediately  
 oppose the permanent magnet poles is unchanged by control  
 current. The air gap in the generator was only 0.007" on  
 inside air gap then re-rotation results in the control  
 current factor. For these reasons, the effect of  
 saturation of the motor iron will not have as much effect  
 on the voltage wave shape as might first be expected. On  
 a machine with a larger air gap, some variation in the output  
 voltage wave shape might be observed.  
 Analysis and experiments were conducted with the motor  
 magnetic material has little effect on the voltage control.  
 This is because the point of saturation of the motor  
 magnetic characteristics curve and the permanent magnet  
 characteristic in the region of voltage control is in the  
 non-saturated region of the motor characteristic. This is



the stator is not saturated due to the flux from the permanent magnet. Since the magnetic characteristics of materials suitable for use in generator stators are practically the same in the unsaturated condition, the graphical solution of the problem does not change.

Had the stator been saturated by the flux from the permanent magnet, the type of magnetic material would have marked effect on the initial voltage and the voltage control. The regulation obtained when the stator is originally saturated is marginal until the control current is increased enough to cause the stator to operate in an unsaturated condition. Figure XIX illustrates this effect.

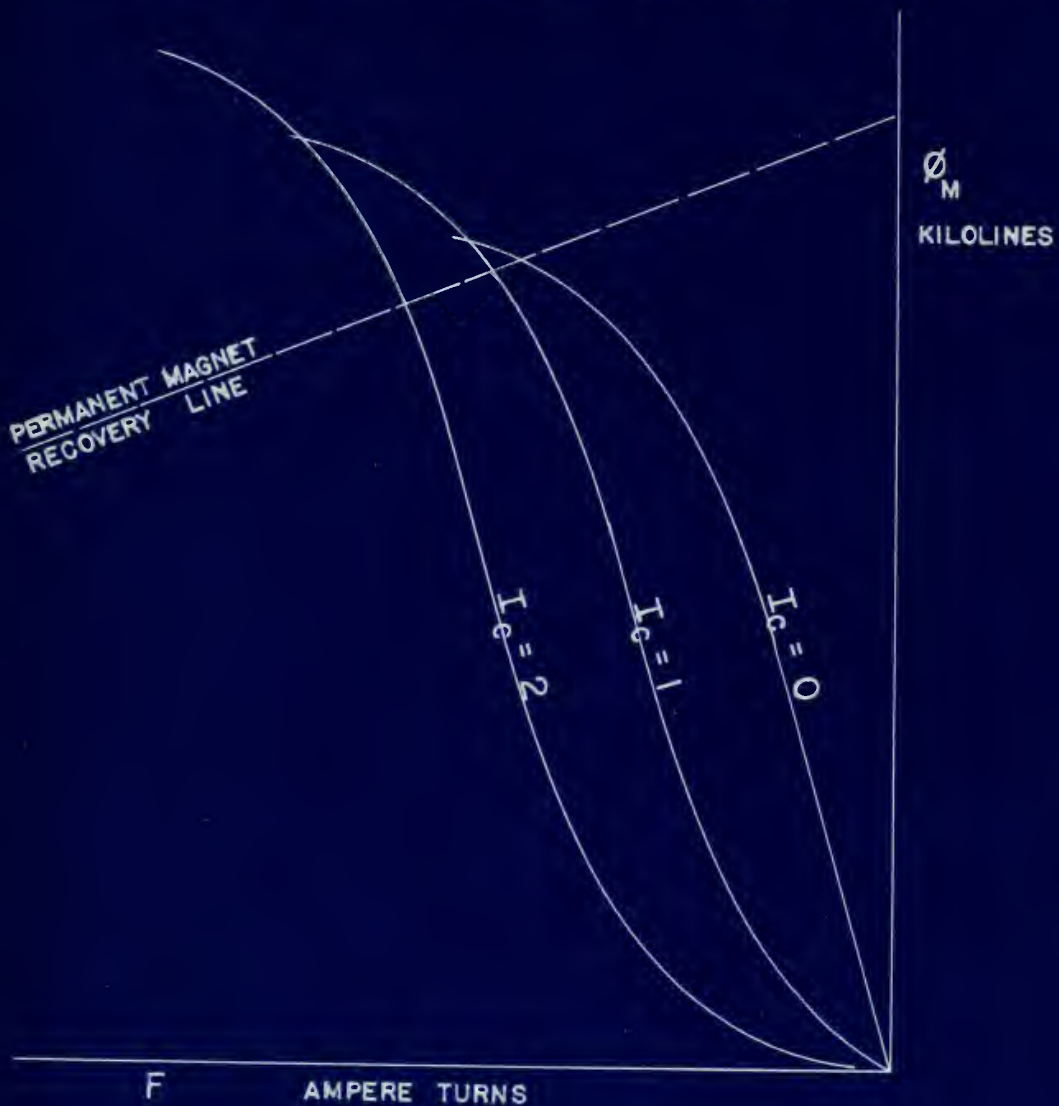
The leakage path seen by the permanent magnet rotor has an effect of major importance on the reduction of air gap flux. The permanent magnet flux solved for as shown in Fig. XV does not represent the air-gap flux which actually induces voltage in the generator windings; leakage flux must be deducted from the permanent magnet flux to obtain air gap flux. The larger the leakage, the more reduction in air-gap flux per unit change in control current can be obtained. That the leakage was underestimated in the calculated results is evident from curve of Fig. XXXI. A method of improving the control obtained is to increase the available flux leakage paths. The effects of decreasing the reluctance of the leakage path facing the magnet is remarkably well demonstrated in Fig. XXXII.

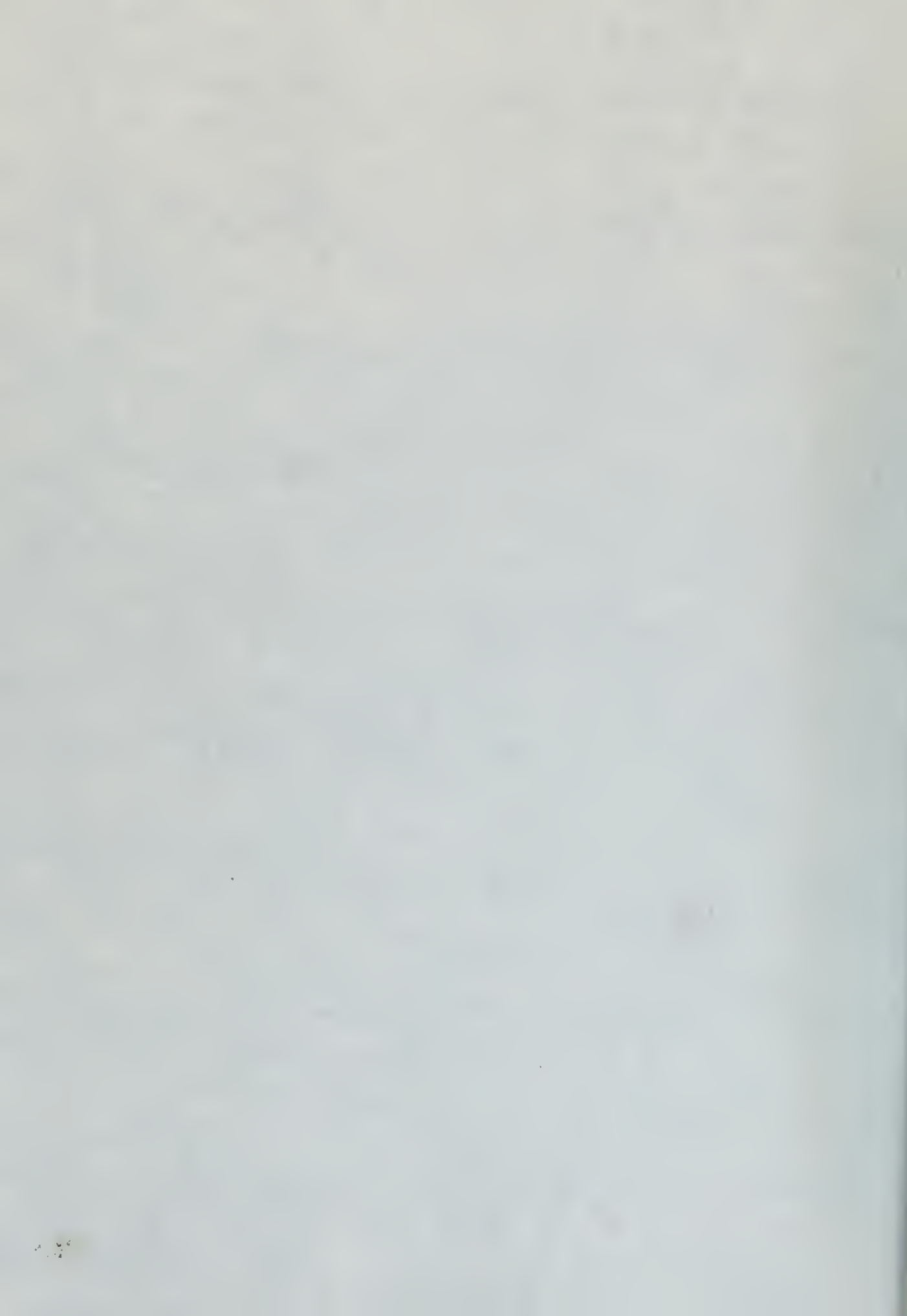
To obtain these curves, several experiments were run

The above is not intended to be the final word on the subject of the Japanese Government's policy. Since the Japanese Government's policy is a subject of international concern, it is necessary to have a clear understanding of the Japanese Government's policy on this subject. The Japanese Government's policy is a subject of international concern, and it is necessary to have a clear understanding of the Japanese Government's policy on this subject. The Japanese Government's policy is a subject of international concern, and it is necessary to have a clear understanding of the Japanese Government's policy on this subject.

## FIGURE XIX

EFFECT OF SATURATION IN THE STATOR  
BEFORE APPLICATION OF CONTROL MMF







with magnetically soft discs separated from the rotor by non-magnetic spacers clamped to both ends of the rotor. It was found that increasing the leakage path by this auxiliary means did increase the per cent voltage regulation. The curves in Fig. XXXII also show that the voltage regulation eventually decreases at higher control currents because the leakage characteristic changes when the discs saturate. No analysis of this phase of the experiment was undertaken because of the uncertain nature of the auxiliary leakage path.

No trouble was encountered due to voltage being induced in the toroidal control winding since the north and south poles of the permanent magnet rotor induced equal and opposite voltages in this continuous winding.

with magnetically self-bias separated from the rotor by  
non-magnetic spacers placed on both sides of the rotor. It  
was found that increasing the leakage path by this auxiliary  
barrier did increase the pot core voltage regulation. The  
curves in Fig. XXXII show that the voltage regulation  
eventually decreases at higher control voltage barriers.  
The leakage characteristic changes when the flux barrier,  
No analysis of this phase of the experiment was undertaken  
because of the uncertain nature of the auxiliary leakage  
path.

No specific was undertaken due to voltage being  
induced in the toroidal control winding since the power was  
switch poles of the permanent magnet rotor induced equal and  
opposite voltages in this continuous winding.

## V. CONCLUSIONS AND RECOMMENDATIONS

The method of analysis devised for the magnetic circuit under the specified conditions of saturation is sound in principle and leads to an acceptable prediction of resultant effects.

It has further been shown that this method is entirely practical for voltage control of a permanent magnet alternator by electrical means. The amount of control obtainable is limited only by the characteristics of the permanent magnet, the design of the magnetic circuit, and by the power one wishes to expend to obtain this control. One advantage of the permanent magnet alternator has, however, been lost. That is, now a source of direct current must be made available, and to obtain direct current from the output requires some rectifying mechanism or circuit.

The amount of control is greatly affected by the reluctance of the leakage paths, and the most obvious method of improving the control for a given power expenditure is to provide an easy leakage path in the magnetic circuit.

Recommendations for further investigation are as follows:

- (1) Seek to improve the stator design to take advantage of the leakage effects to better advantage.
- (2) Perform a more thorough study of the leakage paths to improve upon the approximations used in this analysis.
- (3) Design a circuit for automatic voltage control of



The method of analysis devised for the magnetic circuit under the special condition of operation is based on the principle and leads to an approximate prediction of resultant effects.

It has already been shown that this method is mainly practical for voltage control of a permanent magnet alternator of electrical machine. The amount of control obtainable is limited only by the characteristics of the permanent magnet, the design of the magnetic circuit, and by the type of voltage feedback to obtain this control.

One advantage of the permanent magnet alternator is, however, that it is not a source of direct current and is more available, and to obtain direct current from the output requires some rectifying mechanism or circuit.

The amount of control is greatly affected by the reluctance of the leakage path, and the more obvious method of improving the control for a given power expenditure is to provide an easy leakage path in the magnetic circuit.

Recommendations for further investigation are as follows:

- (1) Work to improve the motor design to take advantage of the leakage circuit to better advantage.
- (2) Perform a more thorough study of the leakage path to improve upon the approximations used in this analysis.
- (3) Design a circuit for permanent voltage control of



the device, using rectified power from the output in a feedback loop. The transient characteristics and power characteristics would be of interest.

- (4) Investigate the effects of alternating current at various frequencies applied to the toroidal winding.[6]
- (5) Apply the principles learned herein to other types of machines where they may be of value. For example, poor voltage regulation of a high-speed induction generator is a serious disadvantage [7], [8]. This method of analysis suggests that the effects of toroidal saturation of an induction generator may be of interest.

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VI. APPENDIX A

DETAILS OF PROCEDURE

VI. APPENDIX A

DETAILS OF PROCEDURE



## DETAILS OF PROCEDURE

### Machine Design:

The design is limited by the characteristics of the existing stator. The physical dimensions, the number of slots, and the shape of the laminations were left unchanged, and a three phase "Y" winding was designed which would generate approximately 90 volts per phase, root mean-square.

The peripheral rim was milled to produce 18 additional slots to recess the outside of the toroidal winding so it would clear the casing when the stator and case were assembled. See Fig. XX.

### Design of the three-phase armature winding: [9]

The design of this winding is based upon two existing pieces of apparatus: the 18-slot stator and the permanent-magnet rotor.

The flux per pole is determined for the "closed circuit" position of the rotor (i.e.: rotor in place in the magnetic circuit) by the method outlined in Section II "PROCEDURE".

Flux per pole,  $\phi_t = 21.7$  kilolines

Assume a field form distribution factor  $f_d = 0.666$

Therefore the "hypothetical total flux" [9]:

$$\phi_t = \frac{\phi_p}{f_d} = \frac{21.74 (4)}{0.666} = 130.9 \text{ kilolines} \quad (20)$$

$$B_g = \frac{\phi_t}{\pi DL} = \frac{130,900}{\pi (2.22)(.875)} = 21520 \text{ lines/inch}^2 \quad (21)$$

Magnetic Design:

The design is limited by the characteristics of the existing motor. The physical dimensions, the number of slots, and the shape of the laminations were left unchanged, and a three phase "Y" winding was designed which would generate approximately 90 volts per phase, two lead-lagging. The peripheral rim was milled to produce 18 radial slots in between the outside of the peripheral winding so it would affect the cooling when the motor had been run assembled. See Fig. IX.

Design of the three phase synchronous winding [3]

The design of this winding is based upon the existing phases of apparatus; the 18 slot motor and the permanent-magnet rotor.

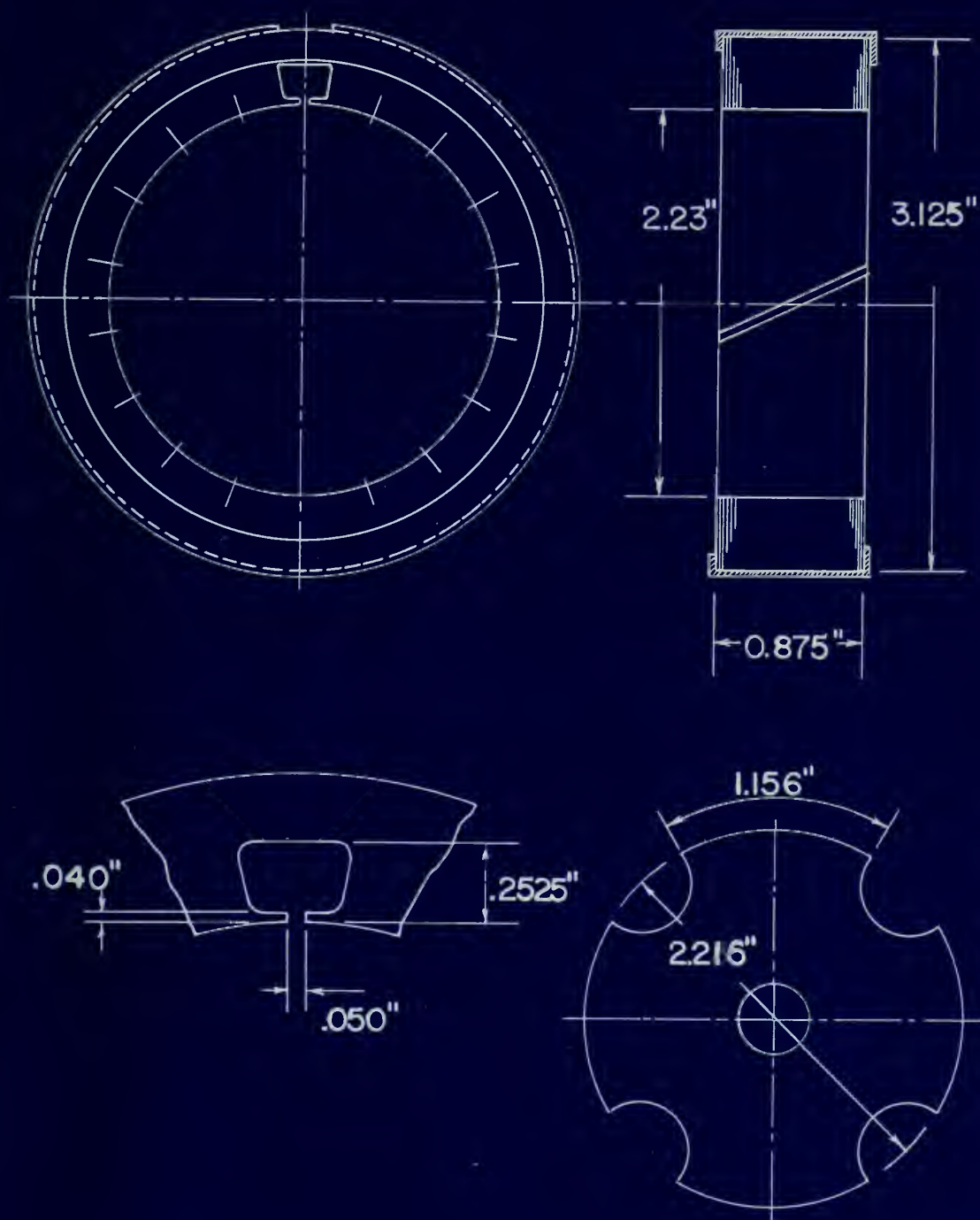
The flux per pole is determined for the closed circuit position of the rotor (i.e. rotor in place in the magnetic circuit) by the method outlined in Section II "PROCEDURE".

Flux per pole,  $\Phi_p = 21.7$  milliwatts  
Assume a field to excitation factor  $F_d = 0.002$   
Therefore the "hypothetical total flux" [3]:

$$\Phi_p = \frac{21.7}{0.002} = 10850 \text{ milliwatts} \quad (10)$$

$$B_p = \frac{\Phi_p}{A_p} = \frac{10850}{\pi (2.5)^2} = 550 \text{ gauss/cm}^2 \quad (11)$$

FIGURE XX  
DETAILS OF STATOR AND ROTOR







DETAILS OF PROCEDURE (cont.)

Assume a winding distribution factor  $C_w$ :

$$\begin{aligned} C_w &= f_b \times f_d \times k_d \\ &= 1.14 \times 0.666 \times 0.956 \\ &= 0.725 \end{aligned} \quad (22)$$

Where  $f_b$  = form factor,

$f_d$  = flux distribution factor

$k_d$  = winding distribution factor

For a pitch winding, the number of conductors in series per phase N:

$$N = \frac{E \times 60 \times 10^8}{\phi_t \times n \times k_p \times C_w} = \frac{90 \times 60 \times 10^8}{130,900 \times 12,000 \times 1 \times 0.725} \quad (23)$$

= 476 conductors in series per phase

The total number of conductors equals  $476 \times 3 = 1428$   
for a winding with one circuit per phase.

The number of conductors per slot is N.

$$N = 1428/18 = 79.2 \quad (24)$$

However with this stator a pitch coil cannot be used,  
since the pitch equals  $4\frac{1}{2}$  slots.

Therefore a coil throw of slots 1 to 5 will be  
necessary:

$$k_p = \sin \left[ \frac{4 \times 90^\circ}{4\frac{1}{2}} \right] = .986 \quad (25)$$

# ESTIMATE OF POWER LOSS

Assume a winding distribution factor  $C_d$

(10)

$$C_d = \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}}$$

$$= 1.11 \times 0.609 \times 0.996$$

$$= 0.775$$

Where  $C_d$  = form factor,

$C_d$  = flux distribution factor

$C_d$  = winding distribution factor

For a pitch winding, the number of conductors in

series per phase is:

(11)

$$Z = \frac{2 \times 60 \times 10^3}{\frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}}} = \frac{2 \times 60 \times 10^3}{\frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}}} = 1.11 \times 0.609 \times 0.996 \times 1.11 \times 0.609 \times 0.996$$

= 440 conductors in series per phase

The total number of conductors per phase is 440

For a winding with one circuit per phase.

The number of conductors per slot is 44.

(12)

$$Z = 1.11 \times 0.609 \times 0.996$$

However this value is not a pitch factor as it is not

since the pitch is not 180°.

Therefore a coil factor of 1.11 is to be

used.

(13)

$$K_p = \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}} = 0.775$$

DETAILS OF PROCEDURE (cont.)

$$\text{and } N = \frac{476}{.986} = 483 \text{ conductors in series per phase.} \quad (26)$$

$$\text{The total number of conductors} = 483 \times 3 = 1449$$

Therefore we will have  $\frac{1449}{18} = 80.3 \approx 80$  conductors per slot, or 40 turns per coil.

Figure XXI shows the wiring diagram for the three-phase winding, and Fig. XXII shows the coil end-connections.

Wire size; and machine rating:

Determination of wire size depends upon space considerations in the slots.

Stator Number 1 (USS Electrical Steel) was limited to 40 turns per coil of Number 26 gauge wire.

$S_a$  = cross sectional area of wire

$S_a$  = .000199 square inches

$A_a$  = allowable current density for short term operation

= 4400 amperes per square inch (twice normal)

$I_a$  = allowable armature current

$$= S_a \times A_a = (.000199) \times (4400) = .875 \text{ amperes.} \quad (27)$$

Machine rating:

$$VA = 3 E I_a = 3 \times 90 \times .875 = 236.2 \text{ volt-amperes.} \quad (28)$$

Stator Number 2 ("HIPERNIK"): In this stator the absence of skew gave more effective slot area, allowing Number 24 gauge wire to be used.



# DETAILS OF WINDING

(10) and  $X = 47 = 60$  conductors in series per phase.

The total number of conductors =  $48 \times 3 = 144$

Therefore we will have  $\frac{144}{18} = 80.3 \approx 80$  conductors

per slot, or 40 turns per coil.

Figure XI shows the winding diagram for the three-

phase winding, and Fig. XII shows the coil end-connections.

Wire size and cooling rating:

Determination of wire size depends upon space

consideration in the slots.

Stator Number 1 (182 electrical degrees) was limited to

40 turns per coil of Number 26 gauge wire.

$S_A = \text{cross sectional area of wire}$

$S_A = .000199 \text{ square inches}$

$A_A = \text{allowable current density for slot temp. operation}$

$= 4400 \text{ amperes per square inch (slot normal)}$

$I_A = \text{allowable ampere current}$

$= S_A \times A_A = (.000199) \times (4400) = .875 \text{ amperes, (11)}$

Cooling rating:

$VA = 3 \times I_A \times V = 3 \times .875 \times 250 = 656.25 \text{ volt-amperes, (12)}$

Stator Number 2 ("WIPER"): IN THIS CASE THE

absence of slot bars was effective slot area, likewise

Number 26 gauge wire is used.



# FIGURE XXI

## DIAGRAM FOR THREE PHASE WINDING

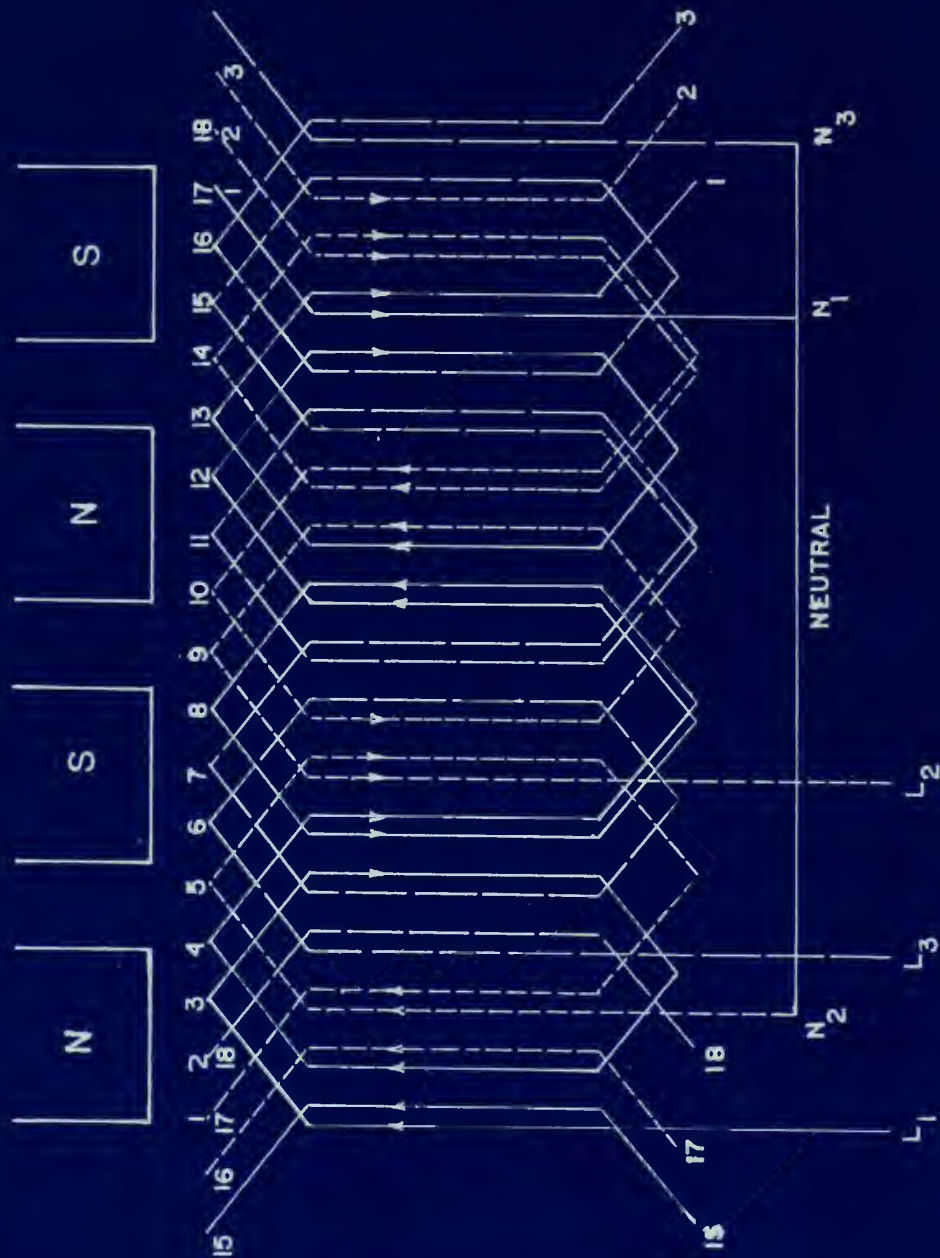
1 1/2 SLOTS PER POLE PER PHASE



- PH. 1
- ⊖ PH. 2
- PH. 3



FIGURE XXII  
GENERATOR COIL END CONNECTIONS  
THREE PHASE - Y CONNECTED







DETAILS OF PROCEDURE (cont.)

$$S_a = .000317 \text{ square inches}$$

$$A_a = 4400 \text{ amperes per square inch}$$

$$I_a = S_a \times A_a = (.000317) \times (4400) = 1.395 \text{ amperes (29)}$$

Machine rating:

$$VA = 3 E I_a = 3 \times 90 \times 1.395 = 377 \text{ volt-amperes (30)}$$

DETAILS OF PRODUCTION (cont.)

$A_2 = 100000$  units

$A_3 = 100000$  units

$I_2 = 100000 \times (1.00000) = 100000$  units

Machine value:

$VA = 100000 \times 1.00000 = 100000$  units

## DETAILS OF PROCEDURE (cont.)

### Details of "Shearing": [5]

A method of obtaining the reluctance characteristics of a magnetic path consisting of a ferromagnetic portion plus an air gap in series is as follows: Neglecting leakage, the flux may be assumed constant throughout the magnetic circuit. Then on coordinates of flux versus magnetomotive force (or magnetic potential drop  $U$ ) we can plot separately the characteristics of the air gap and the rest of the circuit, as shown in Fig. XXIII.

Then, since these two portions of the magnetic circuit are in series, for each value of flux ( $\phi$ ) the magnetic potential drop ( $U$ ) of the entire circuit is the sum of the magnetic potential drops of the two portions. This addition may be done graphically by a process known as "shearing" the characteristic of the ferromagnetic portion into the air-gap line as shown in Fig. XXIV.

## DETAILS OF PROCEDURE (Contd.)

### Details of "Sweeping" [2]

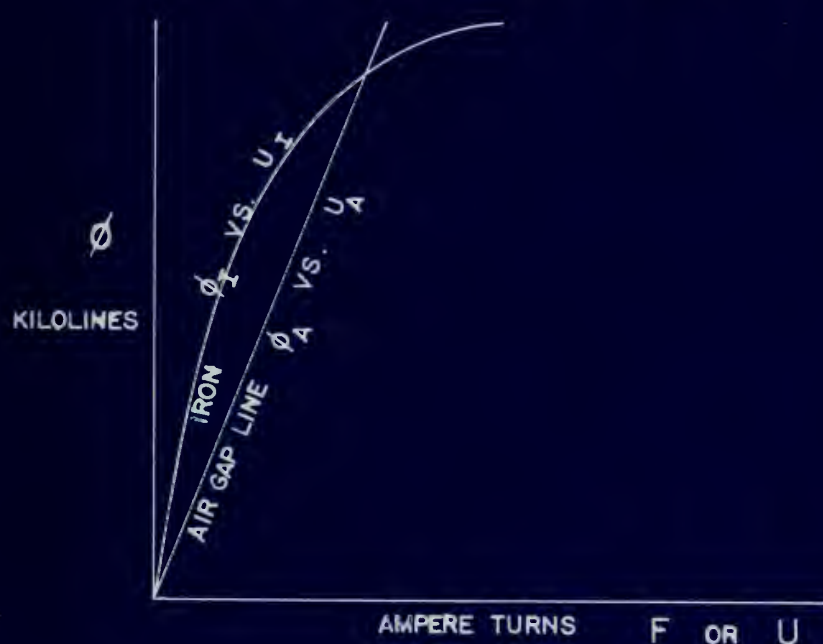
A method of obtaining the minimum concentration of a magnetic gas consisting of a thermomagnetic system gives an air gap in system is as follows: Magnetic leakage, the flux may be removed completely through the magnetic circuit. From an examination of the thermomagnetic force (or magnetic potential drop  $U$ ) we can plot separately the concentration of the air gap and the rest of the circuit, as shown in Fig. XIII.

Then, since these two portions of the magnetic circuit are in series, for each value of flux ( $\Phi$ ) the magnetic potential drop ( $U$ ) of the entire circuit is the sum of the magnetic potential drops of the two portions. This addition may be done graphically by a process shown in "sweeping" the characteristics of the thermomagnetic portion into the air-gap line as shown in Fig. XIV.



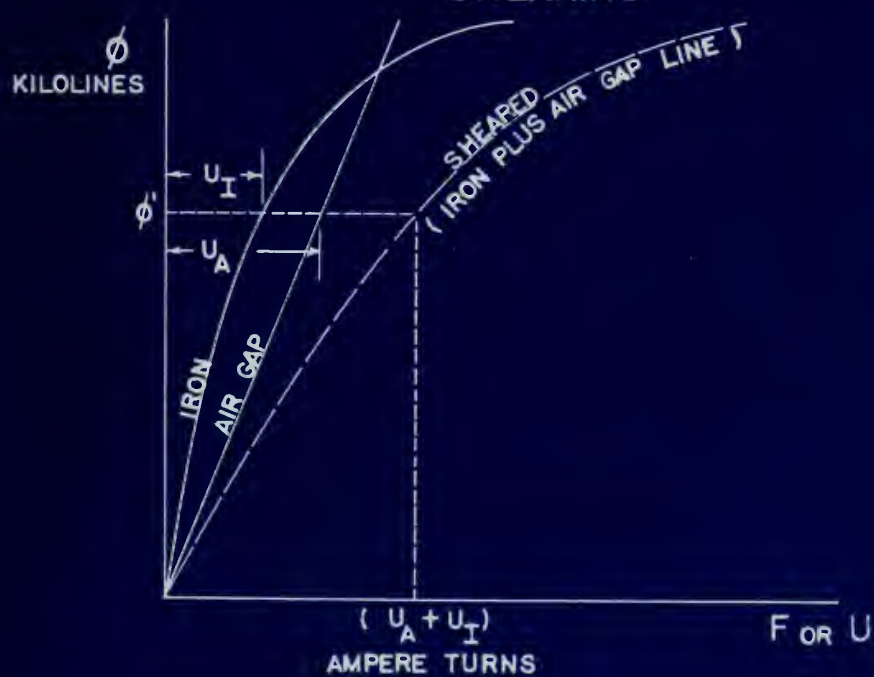
# FIGURE XXIII

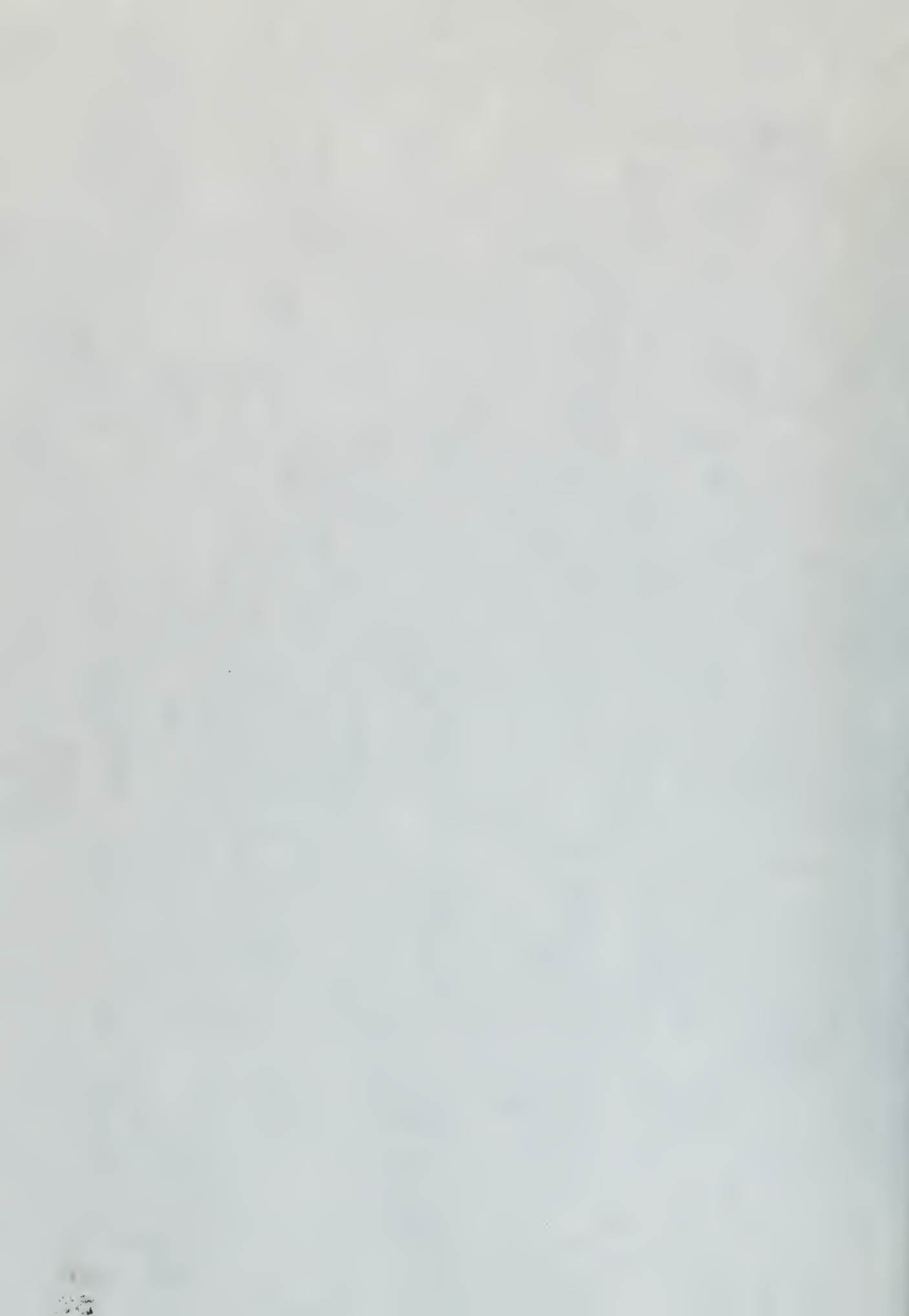
SAMPLE CHARACTERISTICS OF IRON & AIR GAP



# FIGURE XXIV

SHEARING





## DETAILS OF PROCEDURE (cont.)

### Computation of Air-Gap Line:

The dimensions of the armature iron and permanent magnet rotor are as shown in Fig. XX.

The air gap between pole face and stator teeth is:

$$a-g = r_1 - r_m = 1.115'' - 1.108'' = 0.007'' \quad (31)$$

The true air-gap cannot be used directly for computation of the air-gap line in flux vs. magnetomotive force because of the effect of slot openings in the stator. An approximation of an effective air-gap; that is, a fictitious air-gap which would be required if the inside of the stator were made perfectly smooth and the air-gap adjusted so that the flux from the rotor were not changed, is made by the method of Carter [5].

The method of Carter is based on the assumption of slot openings with straight sides and with infinite depth. In the case of the slots under consideration, the slots are semi-closed, not straight, but the method is used on the assumption that the fringing flux will be about the same whether the slots be open or semi-closed since the depth at the edge of a slot tooth is over five times the air gap. This assumption neglects any saturation in the thin parts of the teeth.

Carter's method is outlined below:

$$\sigma = \frac{2}{\pi} \left\{ \tan^{-1} \frac{s}{2\delta} - \frac{\delta}{s} \ln \left[ 1 + \left( \frac{s}{2\delta} \right)^2 \right] \right\} \quad (32)$$

$$C = \frac{t + s}{t + s(1 - \sigma)} \quad (33)$$

$$\delta' = C\delta \quad (34)$$

Composition of Air-Gap Film:

The dimensions of the structure from the permanent magnet rotor are shown in Fig. 11. The air gap between pole tips and rotor teeth is:

$$(31) \quad g = r_1 - r_2 = 1.115 - 1.108 = 0.007$$

The true air-gap cannot be used directly for composition of the air-gap film in the air gap because of the effect of skin openings in the rotor. An approximation of an effective air-gap, that is, a fictitious air-gap which would be required if the teeth of the rotor were made perfectly smooth and the air-gap adjusted so that the flux from the rotor was not changed, is made by the method of Carter [5].

The method of Carter is based on the assumption of slot openings with straight sides and with infinite depth. In the case of the slots under consideration, the slots are semi-closed, not straight, but the method is used on the assumption that the fringing flux will be about the same whether the slots be open or semi-closed since the depth at the ends of a slot tooth is over five times the air gap. This assumption neglects any saturation in the teeth at the ends.

Carter's method is outlined below:

$$(32) \quad \sigma = \frac{2}{\pi} \left\{ \tan^{-1} \frac{g}{2s} - \frac{1}{2} \ln \left[ 1 + \left( \frac{2s}{g} \right)^2 \right] \right\}$$

$$(33) \quad C = \frac{t + 2}{t + 2(1 - \sigma)}$$

$$\delta' = C \delta$$



### DETAILS OF PROCEDURE (cont.)

where:

- s = width of opening between teeth
- $\delta$  = air-gap length
- $\sigma$  = an intermediate factor
- t = length of tooth face
- C = Carter coefficient, the ratio between effective air-gap and actual air-gap
- $\delta'$  = effective air gap

$$\sigma = \frac{2}{\pi} \left\{ \tan^{-1} \frac{0.05}{2 \times 0.007} - \frac{0.007}{0.05} \ln \left[ 1 + \left( \frac{0.05}{2 \times 0.007} \right)^2 \right] \right\} = 0.594 \quad (35)$$

$$C = \frac{0.34 + 0.05}{0.34 + 0.05 (1 - 0.594)} = 1.082 \quad (36)$$

$$\delta' = 1.082 \times 0.007 = 0.00758" \quad (37)$$

The area of each pole face, corrected for air-gap fringing is:

$$A = (\ell_m + \delta')(\ell_f + \delta') = (0.875 + 0.0076)(1.156 + 0.0076) \quad (38)$$

$$= 1.03 \text{ in}^2 \quad (39)$$

The length of two air gaps in series is:

$$2 \times 0.00758 = 0.0152" \quad (40)$$

The slope of the air-gap line is:

$$\frac{\phi}{F} = \frac{\mu_r A}{2 \delta'} \quad (41)$$

where:  $\mu_r$  = the permeability of free space  
= 3.192 in mixed English units

$$\frac{\phi}{F} = \frac{3.192 \times 1.03}{0.0152} = 216 \frac{\text{Lines}}{\text{Amp-Turn}} \quad (42)$$

# RELATION OF PROPERTIES (cont.)

where:

- 1 = width of opening between logs
- 2 = air-gap length
- 3 = an intermediate factor
- 4 = length of each log
- 5 = (center coefficient, the ratio between effective air-gap and actual air-gap)
- 6 = effective air-gap

(25)

$$400.0 = \left\{ \left[ \left( \frac{0.02}{0.001} \right) + 1 \right] \ln \frac{0.001}{0.02} - \frac{0.02}{0.001} \tan^{-1} \frac{0.02}{0.001} \right\} \frac{1}{0.001}$$

(26)

$$C = \frac{0.02 + 0.02}{0.02 + 0.02(1 - 0.02)} = 1.02$$

(27)

$$2' = 1.02 \times 0.001 = 0.00102$$

The area of each side face, converted for air-gap

is:

(28)

$$A = (2' + 2) \left( \frac{0.02}{0.001} + 0.001 \right) = (2 + 0.002)(1.02 + 0.001)$$

(29)

$$2' = 1.02 \ln$$

The length of two air gaps in series is:

(30)

$$2 \times 0.00102 = 0.00204$$

The slope of the air-gap line is:

(31)

$$\frac{A}{2} = \frac{1}{2}$$

where:  $A$  = the perpendicular of two sides  
 $2$  = 2.102 in which square enters

(32)

$$\frac{1}{2} = \frac{2.102 \times 1.02}{0.012} = 175 \frac{\text{inches}}{\text{log-foot}}$$

## DETAILS OF PROCEDURE (cont.)

### Estimate of Flux Leakage

Leakage flux can be estimated by several methods [6], but in any case the estimate should be checked by actual experiment. For an approximation of the slope of the leakage line, the reluctance of the stator iron is neglected. The short air-gap between the rotor and stator is neglected because the area of this air gap in series with the leakage path cannot be determined and is small compared to the remainder of the leakage path. Only the reluctance in the air between the edges of the teeth is considered as shown in Fig. XXV.

Assume, due to fringing, the area of the gap between teeth edges is twice the area of the edge of a tooth.

The leakage flux of the USS Electrical Grade stator will not be the same as that of the HIPERNIK stator because the former has a slot skew of one slot pitch between stator ends whereas the latter stator has no skew.

For the skewed stator, referring to the dimensions shown in Fig. XX, the length of a tooth edge is:

$$l = \sqrt{(0.875)^2 + (0.34 + 0.05)^2} = 0.958 \quad (43)$$

The leakage line is:

$$\frac{\phi}{F} = \frac{3.192 \times 0.958 \times 0.04 \times 2}{0.05} = 4.9 \quad \frac{\text{Lines}}{\text{Amp-Turn}} \quad (44)$$

Since the rotor sees two of these paths in parallel, the slopes of the leakage line is:

$$\frac{\phi}{F} = 2 \times 4.9 = 9.8 \quad \frac{\text{Lines}}{\text{Amp-Turn}} \quad (45)$$



# DETAILS OF PROCEDURE (cont.)

## Rejection of First Leakage

Leakage lines can be estimated by several methods [5],

but in any case the estimate should be checked by actual

experiment. For an approximation of the slope of the

leakage line, the relationship of the error term is

neglected. The error air-gap between the rotor and stator is

neglected because the area of this air-gap is smaller than the

leakage path cannot be determined and is usually assumed to

the relationship of the leakage path. Only the relationship in

the air between the edges of the teeth is considered as

shown in Fig. XIV.

Assume, due to rounding, the area of the gap between

teeth edges is twice the area of the edge of a tooth.

The leakage line of the 100 Electrical Degree sector

will not be the same as that of the 180-degree sector

because the former has a slot width of one slot pitch

between adjacent slots whereas the latter sector has no slots.

For the closed sector, referring to the dimensions

shown in Fig. IX, the length of a tooth edge is:

$$(42) \quad l = \sqrt{(0.875)^2 + (0.75 + 0.05)^2} = 0.953$$

The leakage line for

$$(43) \quad \frac{L}{\Delta \theta} = \frac{0.953 \times 0.953 \times 0.04 \times 2}{0.05} = 4.9$$

Since the rotor area two of these paths is involved,

the slope of the leakage line is:

$$(44) \quad \frac{L}{\Delta \theta} = 2 \times 4.9 = 9.8$$



### DETAILS OF PROCEDURE (cont.)

In addition to leakage between teeth edges, the skewed stator has another leakage path due to a tooth in the gap between adjacent poles which partially overlaps each of the adjacent pole faces as shown by the shaded areas in Fig. XXVI.

The area of each of the triangular shaped air gaps (which are in series) is:

$$A = \frac{1}{2} \left( \frac{1}{4} t \right) \left( \frac{1}{4} l_i \right) = \frac{1}{32} (0.34)(0.875) = 0.0093 \text{ in}^2 \quad (46)$$

and

$$\frac{\phi}{F} = \frac{3.192 \times 0.0093}{2 \times 0.007} = 2.12 \quad \frac{\text{Lines}}{\text{Amp-Turn}} \quad (47)$$

This leakage path can occur only between one pair of adjacent poles at one time; that is, the value  $\frac{\phi}{F} = 2.12$  is not doubled since there is no similar path at the other edge of a pole at any one instant.

The total slope of the leakage line for the skewed stator is

$$\frac{\phi}{F} = 9.8 + 2.12 = 11.92 \quad \frac{\text{Lines}}{\text{Amp-Turn}} \quad (48)$$

since the slopes 2.12 and 9.8 are added as paralleled circuit elements.

For the stator without skew, the slope of the leakage line is considered to be:

$$\frac{\phi}{F} = (2) \frac{3.192 \times 0.875 \times 0.04 \times 2}{0.05} = 8.94 \quad \frac{\text{Lines}}{\text{Amp-Turn}} \quad (49)$$

# DETAILS OF THE PROBLEM

In addition to the jump between each page, the above error has another feature which is a result of the way between adjacent pages which partially overlap each of the adjacent pages. This is shown by the number given in Fig. XVI.

The error of each of the 12 adjacent pages is given (which are in series) in

$$(36) \quad A = \frac{1}{2} \left( \frac{1}{4} + \frac{1}{4} \right) = \frac{1}{2} \left( \frac{1}{2} \right) = 0.25 \text{ in.}$$

$$(37) \quad \frac{\text{Time}}{\text{Area}} = \frac{0.0001 \times 0.0001}{0.0001} = 0.1 \text{ in.}$$

The error between each page is about half the error of adjacent pages at the start; thus the value  $\frac{1}{2} = 0.12$  is not doubled since there is no additional error at the end of a page at the end of the jump.

The total error of the system is for the above

$$(38) \quad \frac{\text{Time}}{\text{Area}} = 0.12 + 0.12 = 0.24 \text{ in.}$$

Since the error 0.12 and 0.12 are added as parallel errors of adjacent pages.

For the error between each, the error of the jump is also is considered in the

$$(39) \quad \frac{\text{Time}}{\text{Area}} = 0.24 + 0.24 = 0.48 \text{ in.}$$

FIGURE XXV  
PATH ASSUMED FOR LEAKAGE  
COMPUTATIONS

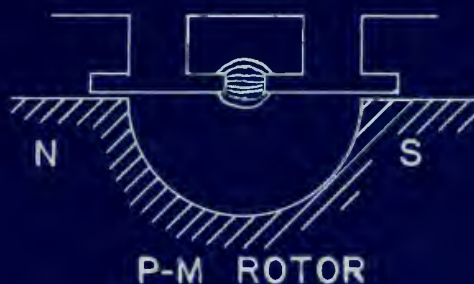
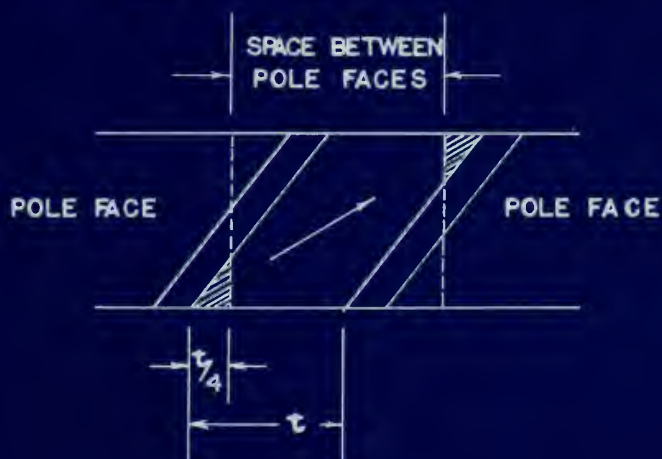
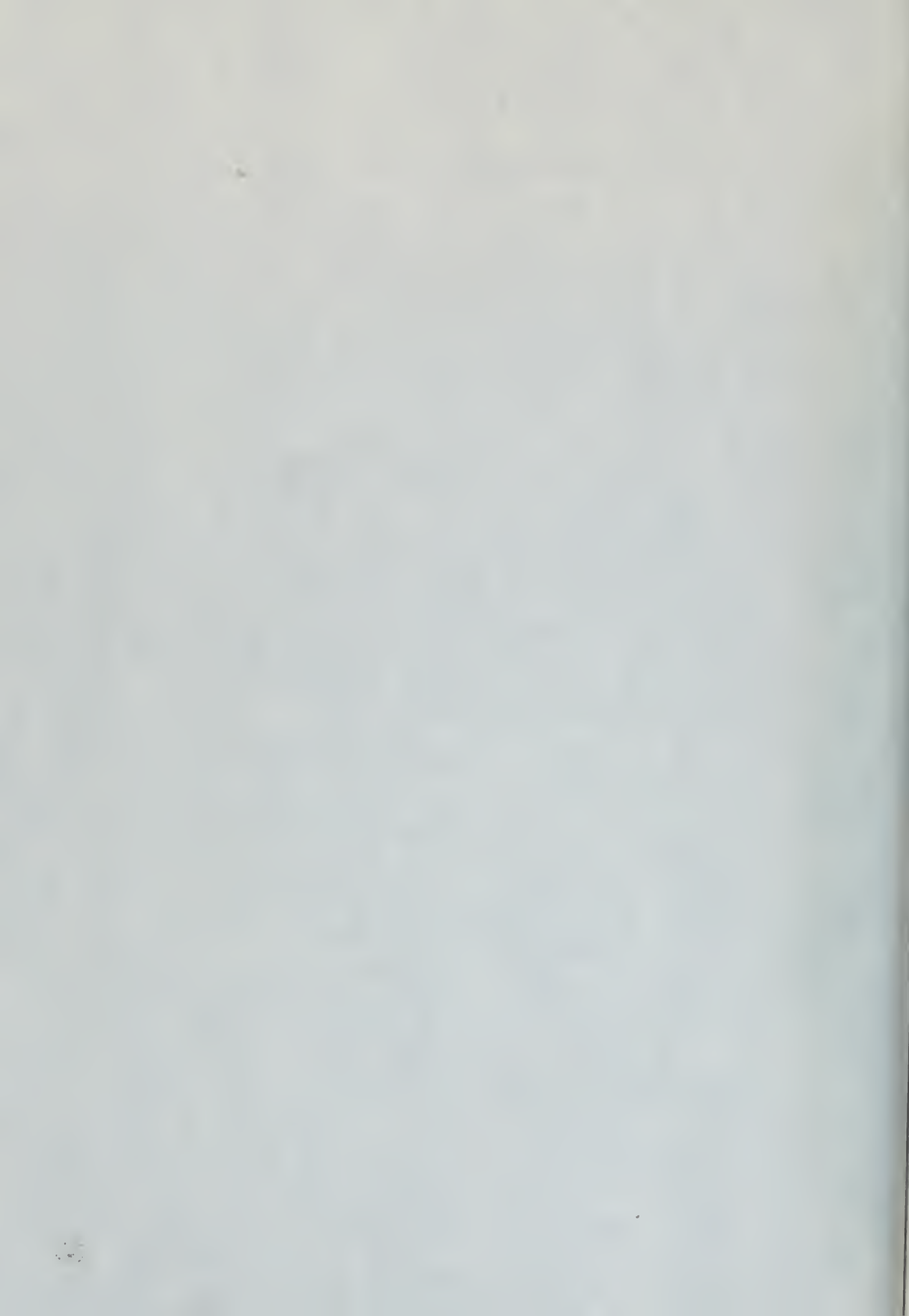


FIGURE XXVI  
DEVELOPED SECTION OF STATOR

SHOWING LEAKAGE PATH ALONG LENGTH OF ONE TOOTH  
DUE TO SLOT SKEW







VI. APPENDIX B

DETAILS OF CALCULATED DATA

VI. APPENDIX B

DETAILS OF CALCULATED DATA

DETAILS OF CALCULATED DATA

TABLE I

Plot of the demagnetization curve of Alnico VI in terms of  
Flux and Magnetomotive force

Flux Density (kilogauss) B	Flux $\phi_m$ (kilolines) $BA \times 6.45$	Magnetizing Force $H$ : (amp-turns/in.)	Magnetomotive Force, F, or Mag. Potential difference U, (amp-turns) $H \times L_m$ $H \times 2.78"$
10.3	67.3	0	0
9.98	65.2	100	278
9.50	62.0	200	556
8.99	58.65	300	833
8.20	53.60	400	1113
7.05	46.00	500	1390
5.20	34.0	600	1669
3.75	24.5	650	1807
2.00	13.05	700	1945
0.0	0.0	750	2085

# TABLE 1

TABLE 1

Plot of the degradation curve of Amino VI in terms of  
Time and Temperature

Time (min)	Temperature (°C)	Residual Amino VI (%)	Residual Amino VI (%)
0	100	100	100
10	100	95	95
20	100	90	90
30	100	85	85
40	100	80	80
50	100	75	75
60	100	70	70
70	100	65	65
80	100	60	60
90	100	55	55
100	100	50	50



DETAILS OF CALCULATED DATA (cont.)

Plot of magnetization curve of USS Electrical Steel in terms of flux and magnetic potential drop:

Flux density (Kilogauss) multiplied by effective cross section and a conversion factor 6.45 equals flux in kilolines:

$$\phi = B \times A \times 6.45 = B \times .156 \times 6.45 \quad (50)$$

Magnetizing force H (Oersteds) multiplied by the length of the magnetic path and the conversion factor 2.01 equals magnetic potential drop U in ampere turns:

$$U = H \times L \times 2.01 = H \times 2.25 \times 2.01 \quad (51)$$

TABLE II

26 Gauge USS Electrical

$\phi$ (kilolines)	U (amp-turns)
0	3.15
4.68	4.28
6.24	4.73
7.80	6.30
9.36	7.20
10.92	11.25
11.70	14.25
12.50	21.6
13.26	32.6
14.05	54.0
14.82	88.9
15.60	157.6
16.39	239
17.18	446
17.95	619

# INITIAL ON CALIBRATED DATA (cont.)

Plot of magnetization curves of the elements used in the

of flux and magnetic potential drop

After density (kilograms) multiplied by effective cross

section and a conversion factor 0.48 equals flux in

kilolines

$$(52) \quad \Phi = B \times A \times 0.48 = B \times 1.00 \times 0.48$$

Magnetizing force H (Oersteds) multiplied by the length of

the magnetic path and the conversion factor 0.01 equals

magnetic potential drop U in ampere turns

$$(51) \quad U = H \times L \times 0.01 = H \times 2.57 \times 0.01$$

## TABLE II

IN GAUSS PER KILOLINE

$\Phi$  (kilolines)       $U$  (amp-turns)

17.90	3.45
17.10	3.30
16.30	3.15
15.50	3.00
14.70	2.85
13.90	2.70
13.10	2.55
12.30	2.40
11.50	2.25
10.70	2.10
9.90	1.95
9.10	1.80
8.30	1.65
7.50	1.50
6.70	1.35
5.90	1.20
5.10	1.05
4.30	0.90
3.50	0.75
2.70	0.60
1.90	0.45
1.10	0.30
0.30	0.15

DETAILS OF CALCULATED DATA (cont.)

TABLE III

Magnetic Circuit Dimensions

Area of magnet pole-face = 1.011 sq. in.

Minimum area of stator path = 0.156 sq. in.

Length of mean rotor flux path = 2.78 inches.

Length of air gap = 0.007 inches (at each pole face)

Total effective length of air gap = 0.0154 inches

Length of stator (saturable) path = 2.25 inches

DETAILED RE-CALCULATED DATA (contd.)

TABLE III

Rectangular Ditch

Area of water flow = 1.071 sq. ft.  
Minimum area of water flow = 0.156 sq. ft.  
Length of mean water flow path = 2.75 inches.  
Length of air gap = 0.007 inches (at each pole head)  
Total effective length of air gap = 0.014 inches  
Length of water (assumed) path = 2.75 inches



DETAILS OF CALCULATED DATA (cont.)

TABLE IV

Plot of the magnetization curve of HIPERNIK in terms of  
flux and magnetic potential drop

Conversion factors same as on previous page:

B (Kilogauss)	$\phi$ (kilolines)	H (Oersted)	U (amp-turns)
0	0	0	0
9.6	9.65	0.2	.911
10.6	10.65	0.4	1.82
11.2	11.25	0.6	2.73
11.6	11.68	0.8	3.64
11.9	11.98	1.0	4.55
12.1	12.18	1.2	5.56
15.2	15.29	20.0	91.1
15.75	15.85	40.0	182.0
15.85	15.95	60.0	273
15.9	16.0	80.0	364
16.0	16.09	100.0	455

# TABLE OF CONVERSION DATA (Cont.)

## TABLE IV

First of two representations of value of function in terms of  
line and magnetic potential lines

Conversion factors used in all previous pages

W (X-axis)    V (Y-axis)    X (Z-axis)    Y (W-axis)

0	0	0	0
10.0	0.1	0.01	0.001
10.0	0.2	0.04	0.004
10.0	0.3	0.09	0.009
10.0	0.4	0.16	0.016
10.0	0.5	0.25	0.025
10.0	0.6	0.36	0.036
10.0	0.7	0.49	0.049
10.0	0.8	0.64	0.064
10.0	0.9	0.81	0.081
10.0	1.0	1.00	0.100
10.0	1.1	1.21	0.121
10.0	1.2	1.44	0.144
10.0	1.3	1.69	0.169
10.0	1.4	1.96	0.196
10.0	1.5	2.25	0.225
10.0	1.6	2.56	0.256
10.0	1.7	2.89	0.289
10.0	1.8	3.24	0.324
10.0	1.9	3.61	0.361
10.0	2.0	4.00	0.400

## DATA

TABLE V

### DETAILS OF STATORS

#### STATOR NO. 1:

Material: USS Electrical Grade Steel, 0.014" Laminations

Toroidal  
Winding: 9 turns per slot, 162 total turns, #24 wire  
0.96 ohms cold  
4.4 millihenries

Three-phase  
Winding: 40 turns per coil of #29 wire  
Line to line Resistance: 23.4 ohms (cold)  
Skewed one slot pitch

#### STATOR NO. 2:

Material: Hipernik, annealed in Hydrogen atmosphere

Toroidal  
Winding: 11 turns per slot, 198 turns total, #24 wire  
1.11 ohms (room temperature)  
16 millihenries

Three-phase  
Winding: 40 turns per coil of #26 wire  
Line to line resistance: 11 ohms (Rm. Temp)  
9.5 millihenries  
No skew

In both stators the length of the magnetic path was assumed to be 2.25 inches, and the cross sectional area 0.156 square inches.





# FIGURE XXVII GRAPHIC SOLUTION

STATOR NO. 1 - USS ELECTRICAL

ALNICO VI ROTOR



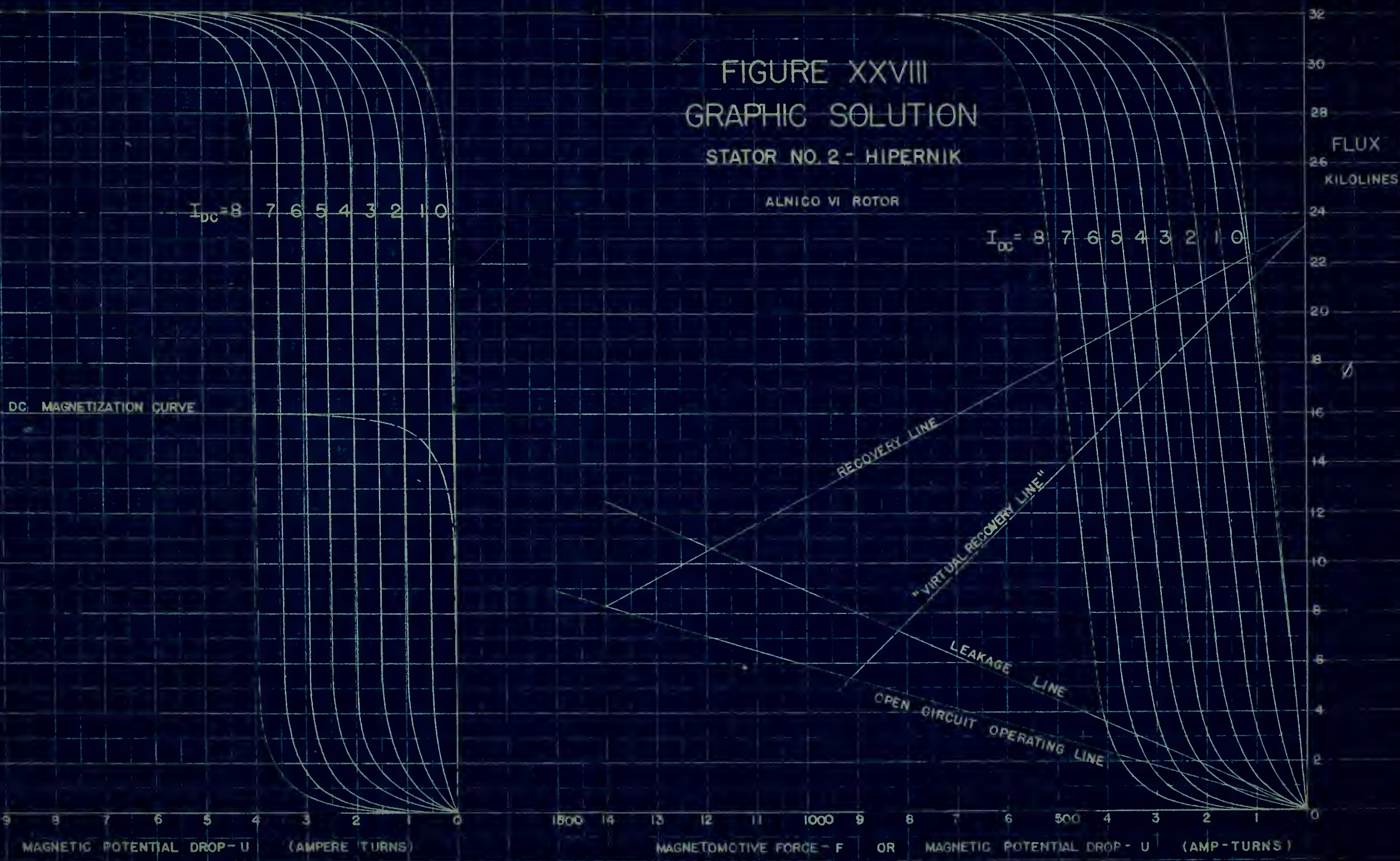
5/18/53  
JLA wxa





# FIGURE XXVIII GRAPHIC SOLUTION STATOR NO. 2 - HIPERNIK

ALNICO VI ROTOR



5/12/53  
SLA







VI. APPENDIX C

SUMMARY OF DATA AND CALCULATIONS

IV. APPENDIX

APPENDIX OF DATA AND CALCULATIONS

## SUMMARY OF DATA AND CALCULATIONS

The summary of data and calculations is presented in the graphs following.

### Figure XXIX:

This figure shows the percentage of initial voltage of the alternator as obtained both by theoretical means and by experiment. The stator laminations are of USS Electrical Grade Steel, and the stack is skewed one slot pitch. The dotted line is the theoretical curve as calculated by the method explained in Section II, "PROCEDURE". Experimental values obtained under various conditions of loading are shown and explained on the figure.

### Figure XXX:

This figure is a summary of raw data for the HIPERNIK stator.

### Figure XXXI:

This figure is similar to Figure XXIX, except that it represents analysis and experiment on a stator whose laminations are of HIPERNIK and whose slots have no skew. The loads are also slightly different as explained on the figure.

### Figure XXXII:

This figure shows the comparison of voltage behavior with and without additional leakage paths being added to the magnetic circuit.

## REMARKS ON DATA AND CALCULATIONS

The summary of data and calculations is presented in

the groups following.

### Figure XXII:

This figure shows the percentage of initial weight of the aluminum as obtained both by theoretical means and by experiment. The atomic calculations are of 100% theoretical weight, and the actual is shown as a dotted line in the theoretical curve as calculated by the method explained in Section II, "PROBABILITY". Experimental values obtained under various conditions of heating are shown and explained on the figure.

### Figure XXIII:

This figure is a summary of data for the HYPERIN

series.

### Figure XXIV:

This figure is similar to Figure XXII, except that it represents analysis and experiment on a series of calculations are of HYPERIN and whose data are shown. The loads are also slightly different as explained in the figure.

### Figure XXV:

This figure shows the comparison of voltage behavior with and without additional leakage paths being added to the magnetic circuit.

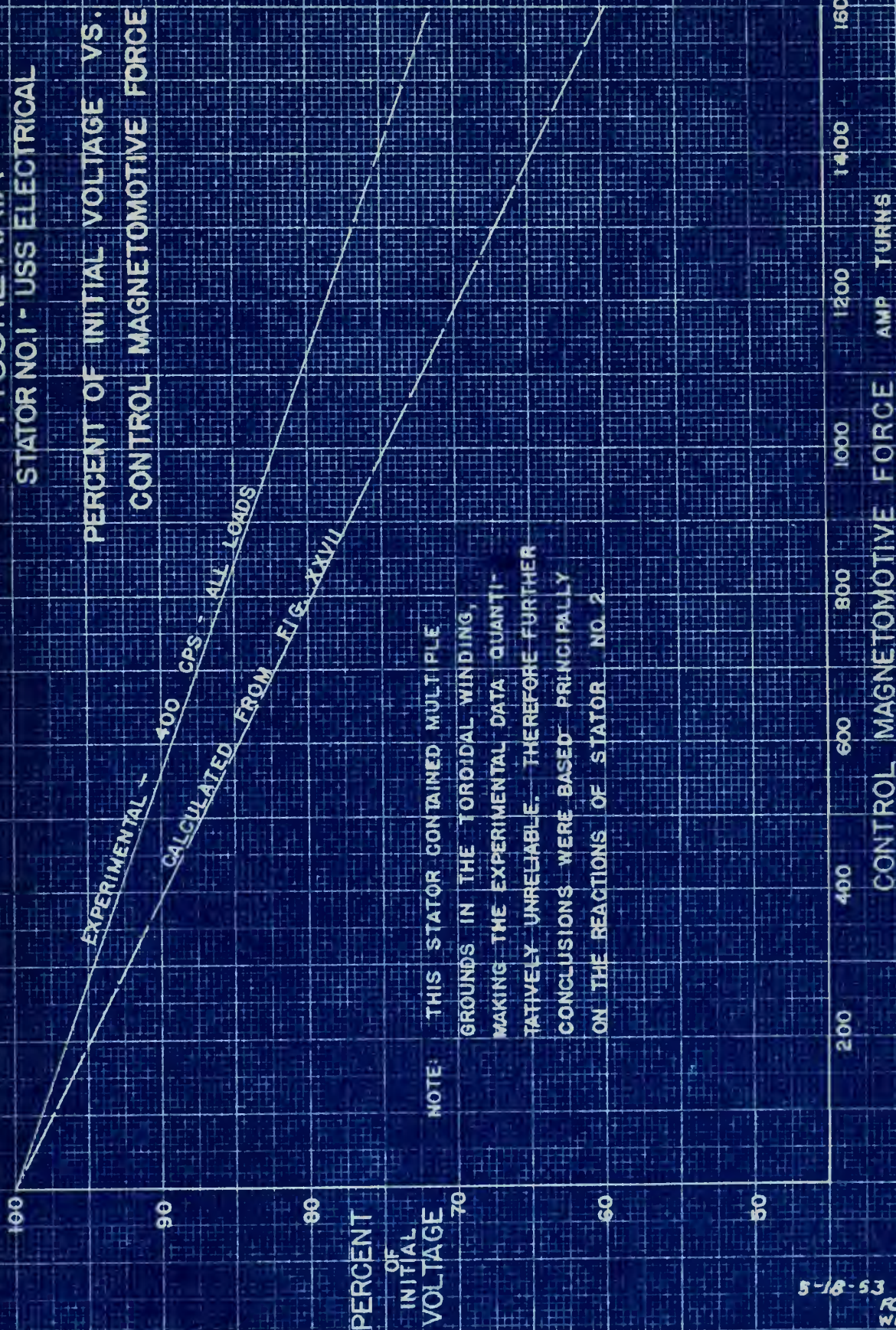


# FIGURE XXIX

## FIGURE XXIX

STATOR NO. 1 - USS ELECTRICAL

PERCENT OF INITIAL VOLTAGE VS.  
CONTROL MAGNETOMOTIVE FORCE









# FIGURE XXX

STATOR NO.2 - HIPERNIK

TERMINAL VOLTAGE VS. CONTROL MMF  
FOR VARIOUS LOADS

400 CPS

VOLTAGE

LINE TO LINE

VOLTS

0

2

3

4

5

6

7

8

DIRECT CURRENT - AMPS

198

396

594

792

990

1188

1386

1584

MAGNETOMOTIVE FORCE - AMP TURNS

FIGURE XXX



6-18-53  
FCA WLA





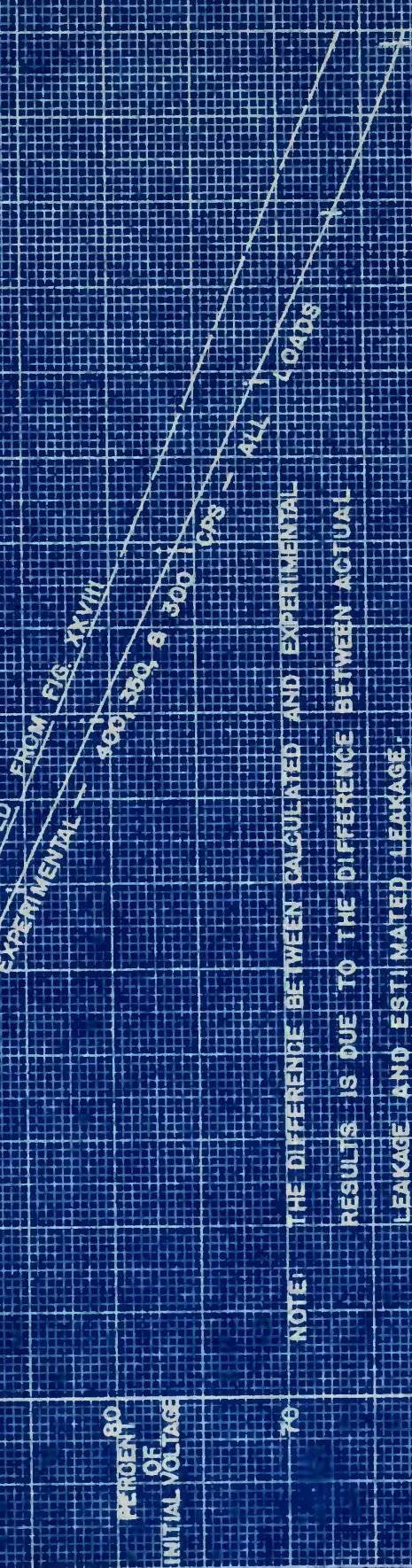


# FIGURE XXXI

STATOR NO. 2 - HIPERNIK

PERCENT OF INITIAL VOLTAGE  
VS.

CONTROL MAGNETOMOTIVE FORCE



NOTE: THE DIFFERENCE BETWEEN CALCULATED AND EXPERIMENTAL RESULTS IS DUE TO THE DIFFERENCE BETWEEN ACTUAL LEAKAGE AND ESTIMATED LEAKAGE.

5-18-53  
WLA RA





# FIGURE XXXI

STATOR NO. 2 - HIPERNIK

PERCENT OF INITIAL VOLTAGE VS. CONTROL MMF  
FOR VARIOUS LEAKAGE CONDITIONS

PERCENT  
OF  
INITIAL VOLTAGE

100

90

80

70

60

50

RUNS NO. 1 - 15  
RUNS NO. 19 - 20  
RUNS NO. 16 - 18

NORMAL LEAKAGE

2 ADDITIONAL LEAKAGE PATHS

1 ADDITIONAL LEAKAGE PATHS

RUNS NO. 1 - 15: NO AUXILIARY LEAKAGE PROVIDED

RUNS NO. 16 - 18: AUXILIARY LEAKAGE CAUSED BY TWO 0.01" SPACERS AND TWO 0.014" LAMINATIONS CLAMPED TO EACH END OF ROTOR - 400 CPS AND 360 CPS

RUNS NO. 19 - 20: AUXILIARY LEAKAGE CAUSED BY TWO 0.010" SPACERS & ONE LAMINATION CLAMPED TO EACH END OF ROTOR

200

400

600

800

1000

1200

1400

1600

CONTROL MMF (AMP TURNS)

# FIGURE XXXII







SUMMARY OF DATA AND CALCULATIONS (cont.)

Figures XXXIII through XXXVIII:

These curves are all derived from the three curves mentioned on the previous page. They are presented as an aid in visualizing the behavior of the alternator under the specified conditions.

Figure XIII (cont.)

These curves are all derived from the same curves  
obtained on the previous page. They are presented as an  
aid in visualizing the behavior of the system under  
the specified conditions.



### VOLTAGE VS. POWER OUTPUT AT 400 CPS

**VOLTAGE VS. POWER OUTPUT  
AT 400 CPS**

STATOR NO. 2 - NORMAL LEAKAGE

The graph plots Terminal Voltage (V) on the Y-axis (60 to 110) against Output Power (Watts) on the X-axis (0 to 140). It includes curves for constant resistive load ( $I_{cc} = 0$  to  $8$ ) and constant inductive load (RUN No. 4 to 6).

Output Power (Watts)	$I_{cc} = 0$ (V)	$I_{cc} = 1$ (V)	$I_{cc} = 2$ (V)	$I_{cc} = 3$ (V)	$I_{cc} = 4$ (V)	$I_{cc} = 5$ (V)	$I_{cc} = 6$ (V)	$I_{cc} = 7$ (V)	$I_{cc} = 8$ (V)	RUN No. 4 (V)	RUN No. 5 (V)	RUN No. 6 (V)
0	110	105	100	95	90	85	80	75	70	-	-	-
20	108	103	98	93	88	83	78	73	68	105	100	95
40	106	101	96	91	86	81	76	71	66	103	98	93
60	104	99	94	89	84	79	74	69	64	101	96	91
80	102	97	92	87	82	77	72	67	62	99	94	89
100	100	95	90	85	80	75	70	65	60	97	92	87
120	98	93	88	83	78	73	68	63	58	95	90	85
140	96	91	86	81	76	71	66	61	56	93	88	83

5-18-53  
FCA WLA

5-18-53  
FCA WLA



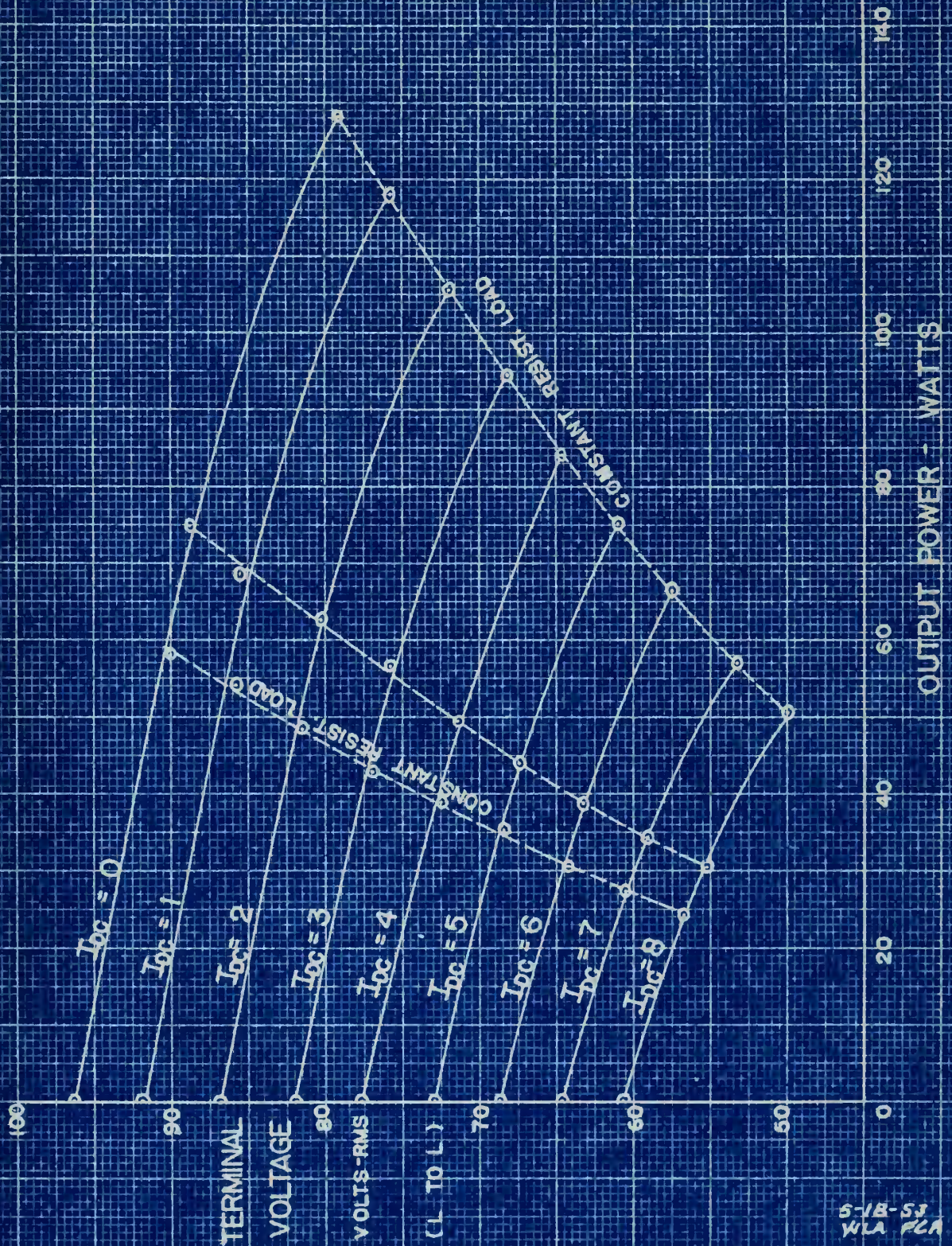




# FIGURE XXXIV

## VOLTAGE VS. POWER OUTPUT AT 350 CPS

STATOR NO. 2 - NORMAL LEAKAGE PATHS





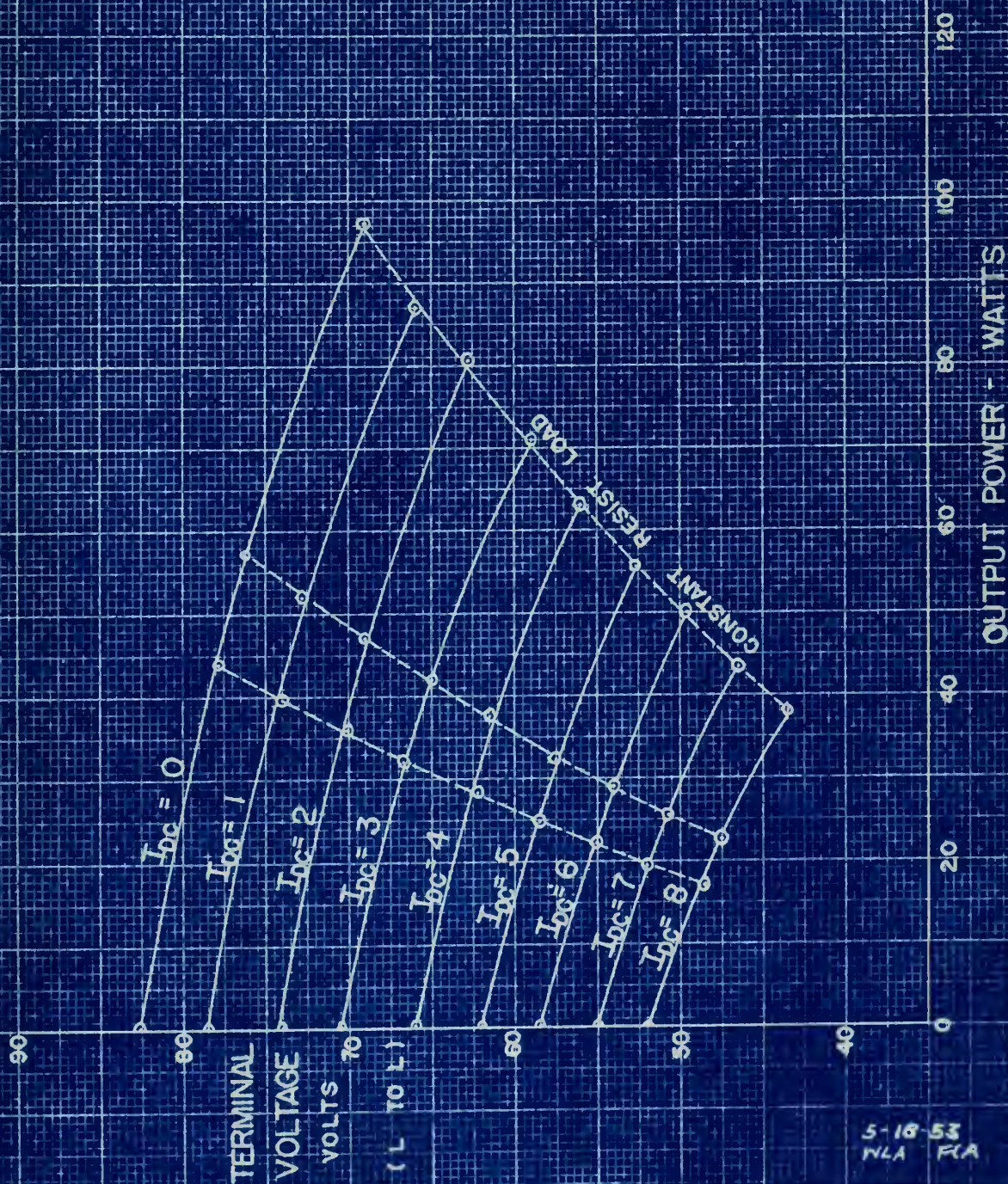




# FIGURE XXXV

VOLTAGE VS. POWER OUTPUT  
- AT 300 CPS

STATOR NO. 2 - NORMAL LEAKAGE PATHS



5-18-53  
NLA F.A.





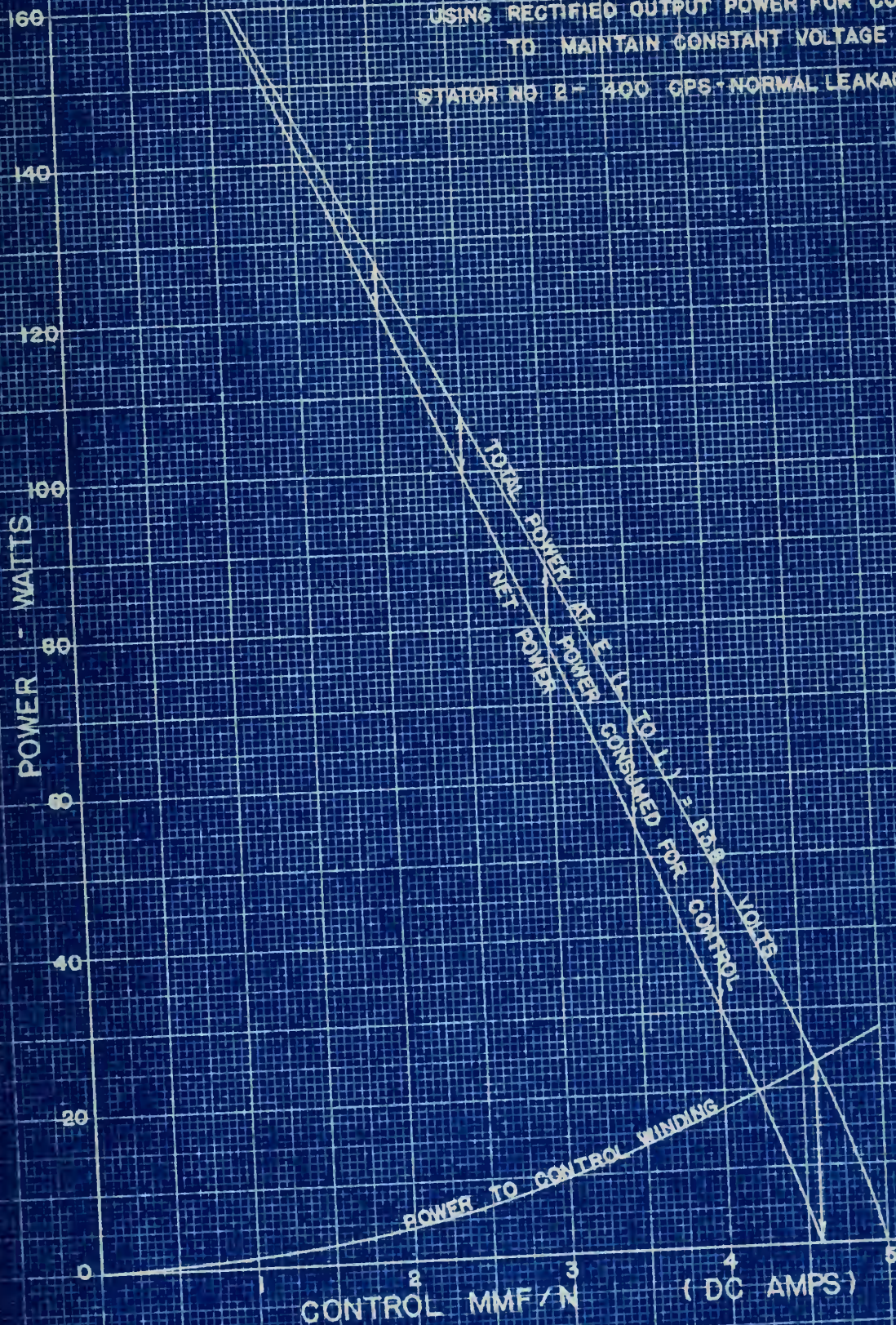


# FIGURE XXXVI

## POWER ANALYSIS -

USING RECTIFIED OUTPUT POWER FOR CONTROL  
TO MAINTAIN CONSTANT VOLTAGE

STATOR NO 2 - 400 CPS - NORMAL LEAKAGE PATHS





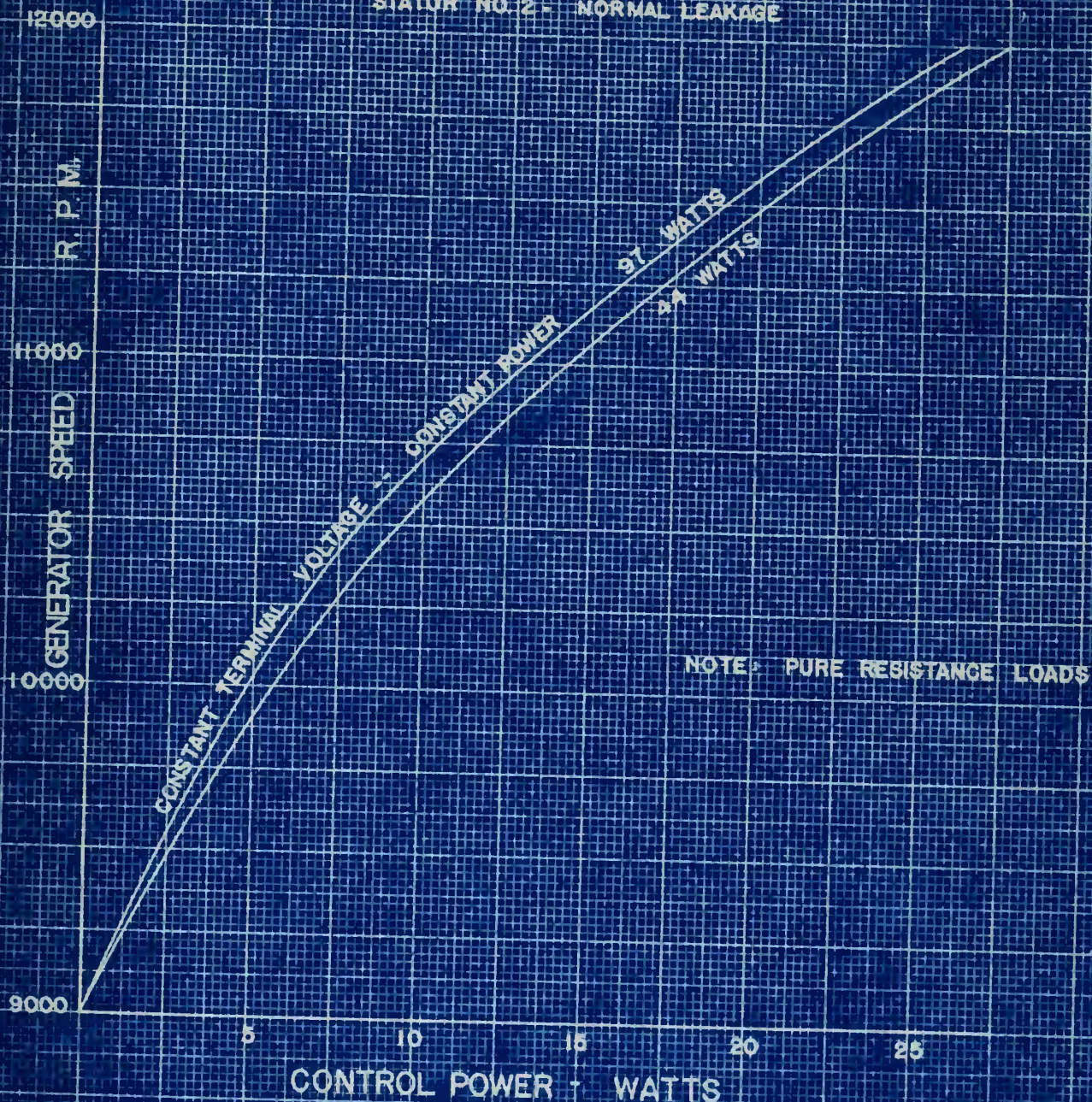




# FIGURE XXXVII

## CONSTANT POWER OUTPUT WITH VARIABLE ALTERNATOR SPEEDS BETWEEN 9000 AND 12000 REV. PER MIN.

STATOR NO. 2 - NORMAL LEAKAGE



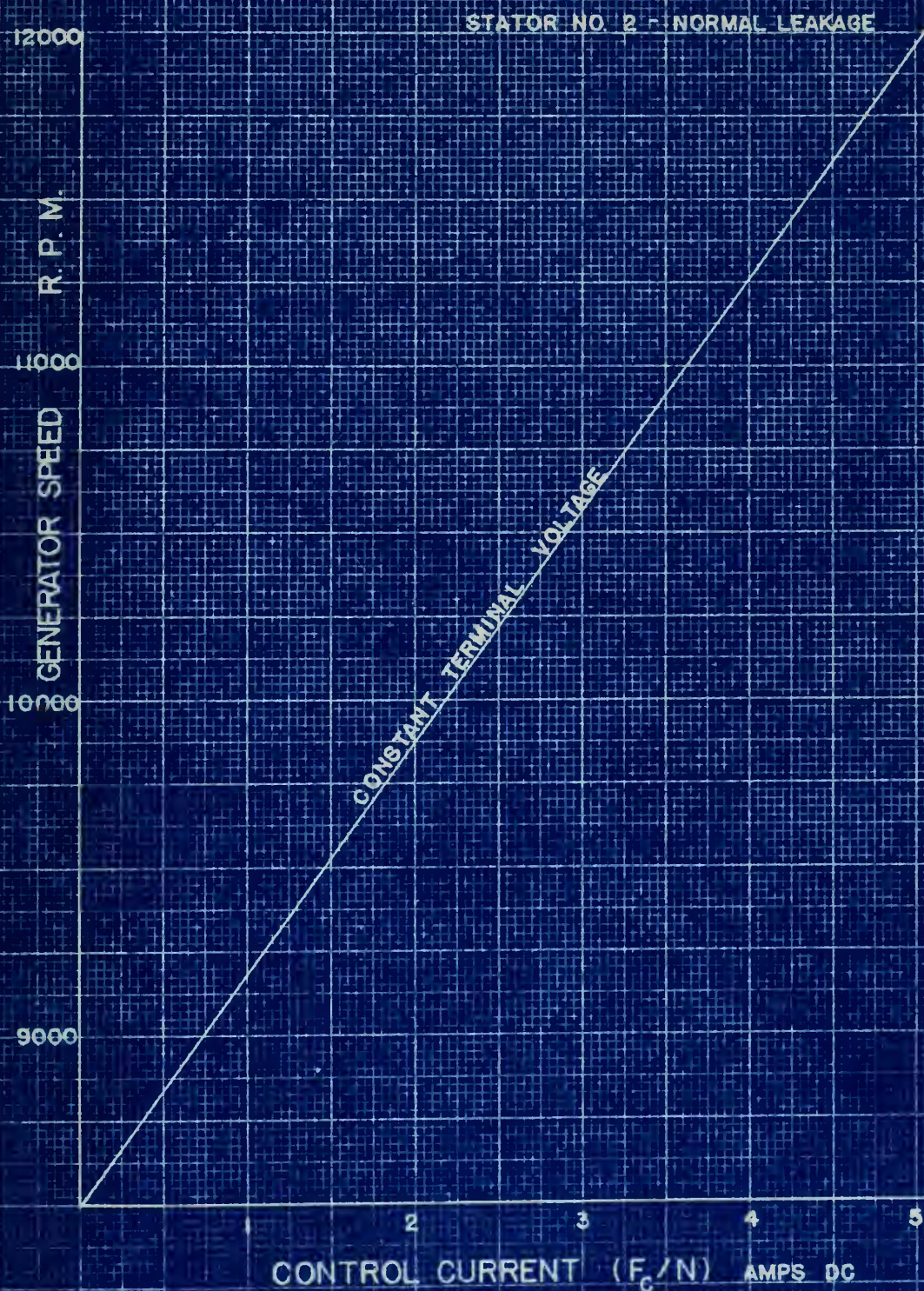






# FIGURE XXXVIII

GENERATOR SPEED VS. CONTROL CURRENT  
AT CONSTANT TERMINAL VOLTAGE



5-18-53  
FCA WLA





VII. APPENDIX D

EXPERIMENTAL DATA



ВЪВЕДЕНИЕ . IIV

ОБЪЯВЛЕНИЕ . IIV

DATA

STATOR NO. 1  
USS ELECTRICAL GRADE STEEL

RUN NO. 1  
NO LOAD- CONSTANT FREQUENCY  
400 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
AMPS	AMP-TURNS	VOLTS	AMPS	WATTS	WATTS	%
0	0	101.5	0	0	No load	100
1	162	99.0	0	0.96	0	97.5
2	324	96.0	0	3.84	0	94.5
3	486	93.0	0	8.64	0	91.5
4	648	89.9	0	15.36	0	88.5
5	810	86.8	0	24.0	0	85.5
6	972	83.9	0	34.56	0	82.6
7	1134	81.0	0	47.04	0	79.7
8	1296	78.1	0	61.44	0	76.9

RMS





DATA

STATOR NO. 1  
USS ELECTRICAL GRADE STEEL

RUN NO. 2  
BALANCED RESISTIVE LOAD—200 OHMS PER PH.  
CONSTANT FREQUENCY— 400 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	amps	Watts	Watts	%
0	0	95.0	.2665	0	42.6	100
1	162	92.9	.260	0.96	40.6	97.6
2	324	90.1	.252	3.84	38.1	94.7
3	486	87.1	.244	8.64	35.7	91.6
4	648	83.9	.236	15.36	33.4	88.2
5	810	81.1	.228	24.0	31.2	85.3
6	972	78.1	.219	34.56	28.8	82.1
7	1134	75.4	.211	47.04	26.7	79.3
8	1296	73.0	.205	61.44	25.2	76.75



DATA

STATOR NO. 1  
USS ELECTRICAL GRADE STEEL

RUN NO. 3

BALANCED RESISTIVE LOAD - 150 OHMS/PHASE  
CONSTANT FREQUENCY - 400 cps

I <sub>dc</sub>	F <sub>c</sub>	V <sub>L to L</sub>	I <sub>a</sub>	P <sub>c</sub>	P <sub>ac</sub>	PERCENT INITIAL V
Amps	Amp-turns	Volts	amps	watts	watts	%
0	0	92.6	.325	0	47.5	100
1	162	90.5	.317	0.96	45.3	97.6
2	324	87.9	.308	3.84	42.6	94.9
3	486	84.9	.298	8.64	40.0	91.6
4	648	82.0	.288	15.36	37.3	88.5
5	810	79.1	.279	24.0	35.0	85.4
6	972	76.5	.269	34.56	32.5	82.6
7	1134	73.6	.259	47.04	30.2	79.4
8	1296	71.0	.251	61.44	28.4	76.7





DATA

STATOR NO. 1  
USS ELECTRICAL GRADE STEEL

RUN NO. 4

BALANCED RESISTIVE LOAD - 100 OHMS/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	89.0	.454	0	61.9	100
1	162	87.1	.444	0.96	59.1	97.9
2	324	84.1	.429	3.84	55.3	94.5
3	486	81.1	.415	8.64	51.8	91.1
4	648	77.6	.398	15.36	47.5	87.2
5	810	74.4	.386	24.00	44.7	83.6
6	972	73.1	.376	34.56	42.4	82.1
7	1134	70.9	.363	47.04	39.5	79.7
8	1296	68.1	.350	61.44	36.8	76.6





DATA

STATOR NO. 1  
USS ELECTRICAL GRADE STEEL

RUN NO. 5

BALANCED INDUCTIVE LOAD- 100 OHMS & 100 Mh/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	93.5	.195	0	11.4	100
1	162	91.2	.191	0.96	10.95	97.5
2	324	88.8	.185	3.84	10.28	95.0
3	486	85.4	.179	8.64	9.62	91.4
4	648	82.8	.174	15.36	9.08	88.6
5	810	80.0	.1675	24.0	8.42	85.6
6	972	77.3	.161	34.56	7.78	82.7
7	1134	74.5	.156	47.04	7.30	79.6
8	1296	72.0	.150	61.44	6.75	77.0



DATA  
 STATOR NO. 2  
 HIPERNIK  
 RUN NO. 1  
 NO LOAD—CONSTANT FREQUENCY  
 400 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_L$ to L Volts	$I_a$ amps	$P_{dc}$ watts	$P_{ac}$ watts	Percent Initial V %
0	0	110.5	0	0	0	100
1	198	104.5	0	1.1	0	94.8
2	396	99.3	0	4.4	0	89.8
3	594	94.0	0	10.0	0	85.0
4	792	88.9	0	17.8	0	80.4
5	990	83.8	0	27.7	0	75.8
6	1188	78.8	0	39.5	0	71.4
7	138.6	73.8	0	54.4	0	66.8
8	1584	69.6	0	71.1	0	63.0

RMS





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 2

NO LOAD  
CONSTANT FREQUENCY - 350 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_L$ to L Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	96.4	0	0	0	100
1	198	92.0	0	1.1	0	95.5
2	396	86.8	0	4.4	0	90.2
3	594	82.0	0	10.0	0	85.2
4	792	77.7	0	17.8	0	80.6
5	990	73.0	0	27.7	0	75.8
6	1188	68.8	0	39.5	0	71.4
7	1386	64.7	0	54.4	0	67.2
8	1584	60.7	0	71.1	0	63.0



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 3

NO LOAD  
CONSTANT FREQUENCY - 300 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_{L \text{ to } L}$ Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	82.6	0	0	0	100
1	198	78.5	0	1.1	0	95.0
2	396	74.0	0	4.4	0	89.6
3	594	70.5	0	10.0	0	85.4
4	792	66.0	0	17.8	0	79.8
5	990	62.1	0	27.7	0	75.2
6	1188	58.5	0	39.5	0	70.8
7	1386	55.0	0	54.4	0	66.6
8	1584	52.0	0	71.1	0	63.0





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 4

BALANCED RESISTIVE LOAD - 139.5 OHMS/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_L$ to L Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	103	.43	0	77.4	100
1	198	97.5	.405	1.1	68.6	94.6
2	396	93.5	.388	4.4	62.9	90.8
3	594	88.7	.368	10.0	56.6	86.1
4	792	82.9	.343	17.8	49.2	80.6
5	990	78.4	.322	27.7	43.4	76.1
6	1188	73.3	.307	39.5	39.4	71.2
7	1386	69.0	.287	54.4	34.4	67.0
8	1584	64.8	.270	71.1	30.5	62.9



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 5

BALANCED RESISTANCE LOAD - 139.5 OHMS/PH  
CONSTANT FREQUENCY - 350 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-Turn	Volts	Amps	Watts	Watts	%
0	0	90.0	.372	0	57.9	100
1	198	85.8	.360	1.1	54.2	95.4
2	396	81.5	.340	4.4	48.4	90.6
3	594	77.0	.320	10.0	42.9	85.6
4	792	72.5	.305	17.8	39.0	80.6
5	990	68.5	.290	27.7	35.2	76.1
6	1188	64.3	.270	39.5	30.5	71.5
7	1386	60.5	.255	54.4	27.2	67.2
8	1584	56.8	.240	71.1	24.1	63.2





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 6

BALANCED RESISTIVE LOAD - 139.5 OHMS/PH  
CONSTANT FREQUENCY - 300 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_{L \text{ to } L}$ Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	77.9	.324	0	43.9	100
1	198	74.0	.308	1.1	39.7	95.0
2	396	70.1	.293	4.4	35.9	90.0
3	594	66.7	.277	10.0	32.1	85.6
4	792	62.2	.260	17.8	28.3	79.8
5	990	58.5	.244	27.7	24.9	75.1
6	1188	55.0	.230	39.5	22.2	70.6
7	1386	52.0	.215	54.4	19.4	66.8
8	1584	48.5	.201	71.1	16.9	62.3



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 7

BALANCED RESISTIVE LOAD - 93 OHMS/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	100.8	.605	0	102.1	100
1	198	95.1	.572	1.1	91.3	94.4
2	396	91.0	.545	4.4	82.9	90.3
3	594	86.1	.518	10.0	74.9	85.5
4	792	81.2	.489	17.8	66.7	80.5
5	990	76.2	.462	27.7	59.5	75.6
6	1188	71.5	.432	39.5	52.0	70.9
7	1386	67.0	.401	54.4	44.9	66.5
8	1584	62.1	.376	71.1	39.5	61.6





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 8

BALANCED RESISTIVE LOAD - 93 OHMS/PH  
CONSTANT FREQUENCY - 350 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	88.8	.518	0	74.9	100
1	198	85.5	.496	1.1	68.6	96.2
2	396	80.2	.472	4.4	62.6	90.2
3	594	75.8	.450	10.0	56.5	85.3
4	792	71.4	.421	17.8	49.5	80.1
5	990	67.4	.397	27.7	43.9	75.8
6	1188	63.3	.373	39.5	38.8	71.3
7	1386	59.1	.350	54.4	34.2	66.5
8	1584	55.2	.330	71.1	30.4	62.1



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 9

BALANCED RESISTIVE LOAD - 93 OHMS/PH  
CONSTANT FREQUENCY - 300 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	76.2	.453	0	57.2	100
1	198	72.8	.432	1.1	52.0	95.8
2	396	69.0	.410	4.4	46.9	90.6
3	594	65.0	.388	10.0	42.0	85.4
4	792	61.5	.367	17.9	37.6	80.9
5	990	57.5	.340	27.7	32.2	75.6
6	1188	54.0	.322	39.5	28.9	70.9
7	1386	50.7	.302	54.4	25.4	66.6
8	1584	47.5	.285	71.1	22.6	62.4





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 10

BALANCED RESISTIVE LOAD - 46.5 OHMS/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	90.0	1.097	0	167.8	100
1	198	86.0	1.05	1.1	153.9	95.6
2	396	81.5	0.99*	4.4	136.9	90.6
3	594	77.3	0.935	10.0	122.0	85.9
4	792	72.8	0.882	17.8	108.5	81.0
5	990	68.8	0.830	27.7	96.1	76.5
6	1188	64.0	0.772	39.5	83.3	71.2
7	1386	60.0	0.725	54.4	73.4	66.7
8	1584	56.0	0.677	71.1	63.9	62.2

\* CHANGE IN AMMETERS WAS REQUIRED



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 11

BALANCED RESISTIVE LOAD - 46.5 OHMS/PH  
CONSTANT FREQUENCY - 350 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	79.1	.957	0	128.2	100
1	198	75.7	.920	1.1	118.1	95.6
2	396	72.0	.870	4.4	105.7	90.9
3	594	68.2	.824	10.0	94.6	86.1
4	792	64.4	.776	17.8	84.1	81.6
5	990	61.0	.734	27.7	75.1	77.1
6	1188	57.5	.690	39.5	66.4	72.6
7	1386	53.2	.640	54.4	57.1	67.2
8	1584	50.0	.601	71.1	50.4	63.1





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 12

BALANCED RESISTIVE LOAD - 46.5 OHMS/PH  
CONSTANT FREQUENCY - 300 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_{L \text{ to } L}$ Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	69.1	.835	0	97.3	100
1	198	66.0	.79	1.1	87.0	95.5
2	396	62.8	.76	4.4	80.6	91.0
3	594	59.0	.713	10.0	70.9	85.4
4	792	56.0	.673	17.8	63.1	81.0
5	990	52.7	.632	27.7	55.7	76.2
6	1188	49.6	.598	39.5	49.9	71.8
7	1386	46.5	.558	54.4	43.4	67.3
8	1584	43.5	.521	71.1	37.9	62.9



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 13

BALANCED INDUCTIVE LOAD- 100 OHMS & 100 MILLIHENRIES/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_{L \text{ to } L}$ Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	102.5	.215	0	13.9	100
1	198	97.5	.204	1.1	12.5	95.1
2	396	92.5	.194	4.4	11.3	90.2
3	594	87.5	.183	10.0	10.0	85.3
4	792	82.5	.172	17.8	8.87	80.5
5	990	78.0	.163	27.7	8.02	76.1
6	1188	73.0	.153	39.5	7.03	71.2
7	1386	69.0	.144	54.4	62.1	67.3
8	1584	65.0	.135	71.1	5.47	63.4





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 14

BALANCED INDUCTIVE LOAD - 100 OHMS & 100 MILLIHENRIES/PH  
CONSTANT FREQUENCY - 350 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	89.0	.206	0	12.7	100
1	198	84.8	.196	1.1	11.5	95.3
2	396	80.5	.186	4.4	10.4	90.5
3	594	76.0	.176	10.0	9.29	85.4
4	792	71.8	.165	17.8	8.17	80.75
5	990	67.0	.156	27.7	7.30	75.3
6	1188	64.0	.147	39.5	6.49	71.9
7	1386	60.0	.136	54.4	5.55	67.4
8	1584	56.5	.130	71.1	5.08	63.5



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 15

BALANCED INDUCTIVE LOAD - 100 OHMS & 100 MILLIHENRIES/PH  
CONSTANT FREQUENCY - 300 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	76.5	.201	0	12.1	100
1	198	72.7	.190	1.1	10.8	95.1
2	396	69.0	.181	4.4	9.83	90.3
3	594	65.1	.171	10.0	8.79	85.1
4	792	61.8	.161	17.8	7.77	80.9
5	990	58.0	.151	27.7	6.84	75.8
6	1188	54.8	.141	39.5	5.96	71.8
7	1386	51.5	.134	54.4	5.39	67.3
8	1584	48.8	.125	71.1	4.69	63.8





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 16

EFFECTS OF INCREASED LEAKAGE:

TWO 0.010" TEFLON SPACERS PLUS TWO 0.014"  
HIPERNIK LAMINATIONS CLAMPED TO EACH END OF ROTOR

NO LOAD  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_{L \text{ to } L}$ Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	89.5	0	0	0	100
1	198	82.8	0	1.1	0	92.5
2	396	76.0	0	4.4	0	84.8
3	594	69.7	0	10.0	0	77.8
4	792	63.6	0	17.8	0	71.0
5	990	58.0	0	27.7	0	64.75
6	1188	52.7	0	39.5	0	58.8
7	1386	48.0	0	54.4	0	53.6
8	1584	43.5	0	71.1	0	48.6



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 17

EFFECTS OF INCREASED LEAKAGE:

TWO 0.010" TEFLON SPACERS PLUS TWO 0.014" HIPERNIK  
LAMINATIONS CLAMPED TO EACH END OF THE ROTOR

BALANCED RESISTIVE LOAD - 100 OHMS/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	80.5	.427	0	54.8	100
1	198	75.0	.400	1.1	48.0	93.2
2	396	69.1	.367	4.4	40.4	85.8
3	594	63.1	.332	10.0	33.1	78.4
4	792	57.8	.306	17.8	28.1	71.9
5	990	52.6	.280	27.7	23.6	65.3
6	1188	47.5	.254	39.5	19.4	59.0
7	1386	42.9	.228	54.4	15.6	53.3
8	1584	39.0	.206	71.1	12.7	48.4





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 18

EFFECTS OF INCREASED LEAKAGE:

TWO 0.010" TEFLON SPACERS PLUS TWO 0.014" HIPERNIK  
LAMINATIONS CLAMPED TO EACH END OF ROTOR

BALANCED RESISTIVE LOAD - 100 OHMS/PH  
CONSTANT FREQUENCY - 350 cps

$I_{dc}$	$F_c$	$V_{L \text{ to } L}$	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	70.0	.375	0	42.2	100
1	198	65.1	.351	1.1	37.0	93.1
2	396	59.8	.322	4.4	31.1	85.5
3	594	55.1	.296	10.0	26.3	78.8
4	792	50.2	.270	17.8	21.9	71.8
5	990	45.5	.246	27.7	18.2	65.0
6	1188	41.5	.223	39.5	14.9	59.4
7	1386	37.5	.200	54.4	12.0	53.6
8	1584	34.0	.180	71.1	9.73	48.6



DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 19

EFFECTS OF INCREASED LEAKAGE:

TWO 0.010" TEFLON SPACERS PLUS ONE 0.014" HIPERNIK  
LAMINATION CLAMPED TO EACH END OF ROTOR

NO LOAD  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$ Amps	$F_c$ Amp-turns	$V_{L \text{ to } L}$ Volts	$I_a$ Amps	$P_{dc}$ Watts	$P_{ac}$ Watts	PERCENT INITIAL V %
0	0	97	0	0	0	100
1	198	91.3	0	1.1	0	94.2
2	396	85.5	0	4.4	0	88.2
3	594	79.6	0	10.0	0	82.1
4	792	73.9	0	17.8	0	76.3
5	990	69.0	0	27.7	0	71.2
6	1188	63.8	0	39.5	0	65.8
7	1386	59.0	0	54.4	0	60.9
8	1584	54.9	0	71.1	0	56.6





DATA

STATOR NO. 2  
HIPERNIK

RUN NO. 20

EFFECTS OF INCREASED LEAKAGE:

TWO 0.010" TEFLON SPACERS PLUS ONE 0.014" HIPERNIK  
LAMINATION CLAMPED TO EACH END OF ROTOR

BALANCED RESISTIVE LOAD - 100 OHMS/PH  
CONSTANT FREQUENCY - 400 cps

$I_{dc}$	$F_c$	$V_L$ to L	$I_a$	$P_{dc}$	$P_{ac}$	PERCENT INITIAL V
Amps	Amp-turns	Volts	Amps	Watts	Watts	%
0	0	88.5	.468	0	65.8	100
1	198	83.2	.442	1.1	58.7	94.1
2	396	78.1	.415	4.4	51.8	88.3
3	594	72.8	.388	10.0	45.2	82.3
4	792	68.0	.362	17.8	39.4	76.9
5	990	63.1	.336	27.7	33.9	71.3
6	1188	58.4	.310	39.5	28.8	66.0
7	1386	53.8	.288	54.4	24.9	60.8
8	1584	50.0	.266	71.1	21.2	56.5



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